THERMAL EFFECTS ON SURFACE FAILURE IN GEARS

By

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I dedicate this thesis to my dear father, mother, wife and son.

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of the University of Florida in Partial Fulfillment of the
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All current standards and design relationships for surface durability of gears are based on contact stress considerations. Thermal effects are considered only for scoring failures when the destruction of the lubricating film occurs as a result of temperature rise Temperature increase on the surface reduces the film thickness and causes the solid to solid contact. The objectives of this dissertation are to consider the mechanism of thermal stress and thermal cycling during tooth contacts for dry and lubricated conditions and its effect on the allowable mechanical and thermal strength for different machining processes and geometrical conditions The main goal is to develop a dimensionless relationship to take into consideration the combined effect of the thermal and mechanical stress in predicting the surface failure of gears for different design, manufacturing and operating parameters The result of the study shows that the gears with low number of pinion teeth and high gear ratios are more influenced by the thermal effects Also the allowable mechanical stress is reduced with decreasing center distance The surface roughness is found to have a significant effect on the temperature rise on asperities but

not on the bulk surface. Fine ground gears are generally less affected by the thermal stress since the heat input is due to viscous sheer. High carbon steel gears are significantly more sensitive to the thermal stress than low carbon steel because of the significant change of their ultimate strength with temperature and their high susceptibility to thermal fatigue and thermal shock.

CHAPTER I
INTRODUCTION

Although most of the failures of gears are surface failures the interaction between the factors influencing these failures is not yet fully understood Furthermore there is no general agreement among the researchers on the effect of lubrication on surface durability The most common types of surface failures are usually classified as pitting wear and scoring.

Pitting and Recent Studies on Pitting of Rolling/Sliding Contacts

In the past there was a tendency to regard pitting as a secondary wear problem and most of the attention focused on macroscopic pitting, which is attributed to contact fatigue Pitting is traditionally considered as a Hertzian fatigue phenomenon which occurs when a fatigue crack is initiated either at the surface of the gear tooth or at a small depth below the surface It is seen in rolling element bearing and gears when the Hertzian pressure exceeds an allowable value The crack usually propagates for a short distance in a direction roughly parallel to the tooth surface before turning up or branching to the surface When the cracks grow to the extent of separating a piece of the surface material a pit is formed When several pits grow together, a larger pit is generally referred to as a spall Metallographic sections and other methods of examination suggest that the micro-pitting cracks and the cracks producing macro-scale pitting have similar morphology The main difference seems to be that of scale

Webster and Norbart [1] investigated the effect of various parameters on a type of progressive fatigue wear known as micro-pitting. They concluded that increasing the

load decreasing specific film thickness and maintaining negative relative sliding all increased the rate of micro-pitting wear. They also reported that micro pitting is almost completely eliminated at very low, but non-zero, slide to roll ratio.

Tallian [2] investigated the role of surface defects in spalling life prediction modeling. His efforts concentrated on micro-spalling, in asperity dimensions. He analyzed surface distress defect formation in rolling contact using the Greenwood-Williamson surface roughness model. He suggests a significant influence on life of several parameters such as EHL film thickness ratio, traction, material fatigue properties and pre service defects. In another paper, Tallian [3] proposed a spalling fatigue life model based on populations of surface defects with depth (severity) distribution according to the Greenwood-Williamson asperity model.

Chen [4] concluded from experimental tests that pitting failure is liable to occur on the contacting parts with a rougher surface. Zhou, Cheng, and Mura [5] presented a micro-macro contact model for surface pitting in rolling and sliding contact. They analyzed the pressures related to asperity interaction and the subsurface stress map along the whole contact area by superimposing the asperity loads on the Hertzian load for a given specimen surface.

Blake and Cheng [6, 7] reported on a surface pitting life model for estimating failure probabilities and service lives of spur gears based on an initial crack size distribution and on possible interaction between cracks and inclusions. An improved model was reported by Blake and Draper [8]. The two-dimensional propagation model was modified to reflect three-dimensional cracks driven by both shear and lubricant pressure effects.

Winter and Oster [9] conducted some tests to examine the influence of lubricants on micro-pitting. Ding, Jones, and Kuhnell [10] investigated the behavior of subsurface cracks in gear teeth. They constructed a finite element model of a number of two dimensional cracks beneath the pitch line of a gear tooth.

Wear and Recent Studies on Wear of Rolling/Sliding Contacts

Wear is a surface phenomenon in which layers of metal are removed or "worn away" more or less uniformly from the contacting surfaces of the gear teeth. Experience indicates that metal is removed in the dedendum area where the maximum negative sliding occurs at the starting point of contact. The pitch line begins to show as an unbroken line. Wear is most commonly assumed to be caused by repeated disturbances of the frictional bonds and an inadequate lubrication film. Because the events that produce wear debris occur at and below the interface of contacting asperities, what is known about wear has been characterized by examining the products of wear, such as wear scars, debris, noise, thermal effect, hardness change, etc.

Adhesive wear (sometimes called scuffing or galling) involves several steps. First, when two surfaces are pressed together, the microscopic bumps on the surfaces squeeze together and form a solid junction when the atoms of the two surfaces bond. When one surface moves relative to the other, the weaker material breaks at some distance from the junction and forms a lump of wear material.

Abrasive wear occurs when a hard particle digs into a softer surface and plows out material. This is called two-body abrasion. Three-body abrasion may happen when free particles are trapped between the two surfaces. As the surfaces move relative to each other, the hard foreign particles plow out material from the softer surface areas. Other

situations are known to occur where the hard foreign particles are imbedded in the softer material and create wear tracks in the harder surface

Lin Cheng and Jang [11] conducted experiments to measure the wear behavior of simulated lubricated gear contacts They reported that the effect of applied load on wear is more significant than the effect of speed They also reported that the oil temperatures increased as the sliding speed or the applied loads are increased.

Kopf [12] investigated the phenomenon of progressive wear which causes a rapid increase in wear rate, distortion of the tooth profiles and the failure of the gear transmission.

Nikolashev [13] proposed a gear train wear analysis method that accounts for the change of the slip coefficient and the width of the contact area as it passes the surface location at which wear is determined He reported that wear at the pitch point of an involute gear exists and increased with an increase in the gear ratio

Drozdov et al [14] reported on a method for the calculation of the work capacity of gear transmissions and proposed a wear criterion based mainly on mechanical considerations Formulas are proposed in their report for calculations of wear intensity of solids

Scoring and Recent Studies on Scoring of Rolling/Sliding Contacts

Rapid wear often results from a failure of the oil film due to overheating of the mesh permitting metal-to-metal contact This contact produces alternate welding and tearing which removes metal rapidly from the sliding surfaces accompanied by transfer of metal from one surface to the other surface This occurs at high sliding velocity and intense surface pressure which cause the frictional heat. Failure of the lubricant is associated with a flash temperature of the lubricant The flash temperature is an

instantaneous temperature rise that occurs on the gear teeth surface due to the frictional heating

Lee and Cheng [15 16] proposed a theory for predicting the onset of scoring failures over a wide range of operating conditions including contacts operating in the boundary lubrication and in the partial elasto-hydrodynamic lubrication regimes They concluded that failures occur when the contact temperatures exceed a certain critical value Experiments were undertaken [17] to support their hypothesis Terauchi [18] reported on extensive experiments on the failure of the tooth surfaces of spur gears due to scoring He examined the main factors influencing the scoring resistance of the gears, such as the number of teeth, tooth profile modification, module, and the mechanical and thermal properties of the gear materials and the lubricants

Matveevsky [19] suggested friction power as a viable scoring criterion for the surfaces of different materials under boundary lubrication conditions. Carper and Ku [20] proposed a methodology based on the critical frictional power criterion for correlating and predicting the scuffing behavior of sliding-rolling disks Bell, Dyson, and Hadley [21] investigated the independent influences of rolling speed and sliding speed on the scuffing of hardened steel discs lubricated by a mineral oil

Macpherson and Cameron [22] investigated the phenomenon of fatigue scoring. They suggest that it is caused by micro cracks and micro pits forming on the surface of heavily loaded contacts, which drain away the oil in the contact.

Studies on Surface Temperature Calculation of Sliding/Rolling Contacts

Townsend and Akin [23] performed gear tooth temperature analysis using a finite element method combined with a calculated heat input, and estimated heat transfer coefficients They also conducted experimental measurements of the average surface

temperatures and instantaneous surface temperatures Obuta Fujita, and Fuji [24, 25] investigated the temperature rise (the flash temperature component and the bulk temperature rise component) of a gear tooth model when a moving heat source with variable heat quantity acted repeatedly at regular time intervals. Rashid and Seireg [26] studied the heat partition and the transient temperature distribution in layered concentrated contacts and developed the empirical formulas based on the numerical results the study

Objective of the Study

All current standards and design relationships for surface durability of gears are based on contact stress considerations Thermal effects are considered only for scoring failures when the destruction of the lubricating film occurs as a result of temperature rise

The proposed study considers the mechanism of thermal stress and thermal cycling during tooth contacts for dry and lubricated conditions and its effect on the allowable mechanical and thermal strength for different machining processes and geometrical conditions The main goal is to develop dimensionless relationships to take into consideration the combined effect of the thermal and mechanical stress in predicting the surface failure of gears for different design, manufacturing and operating parameters

CHAPTER 2

DIMENSIONLESS RELATIONSHIP FOR SURFACE TEMPERATURE

Nominal Temperature Rise at The Start of Contact Zone

In order to investigate the surface damage phenomena of gear teeth in contact, it would first be necessary to calculate the induced thermal and mechanical stresses at the most critical points of the contact cycle. The contact between the pinion and gear teeth surface can be considered as the contact of two cylinders with the same radii of curvature as the tooth surfaces at the contact zone.

The transient temperature, T_c, is given as the sum of the bulk temperature [T_b] and the temperature rise [ΔT] due to frictional heating.

$$T_c = T_b + \Delta T \qquad (2.1)$$

The induced temperature by a moving band of heat source on semi-infinite solid which can be applied to gears in sliding contact, is given by the solution of the governing differential equation for the one dimensional heat conduction equation [27]

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) \qquad (2.2.a)$$

where t = time, sec

T = temperature, ^{0}F

y = coordinate perpendicular to the plane of heat source, in.

ρ= material density, lb/in^{3}

k= coefficient of conductivity, in-lb / in-s ^{0}F

The boundary conditions for half-space are

t at 0; $T(y\ 0)=T_b$ (Bulk temperature)

On the surface of the solid the equation relating the constant frictional power intensity q to the temperature is written as

$$k\left(\frac{\partial T(0\ t)}{\partial_y}\right)=\dot{q}$$

When the effect of the applied heat flux reaches the penetration depth (D) the boundary condition expressing the heat transfer for zero heat flux across the lower plane boundary is expressed as

$$\left(\frac{\partial T(D\ t)}{\partial}\right)=0$$

The solution of the governing differential equation gives the maximum transient temperature of the contact zone as

$$\Delta T = \frac{2q}{\sqrt{\pi k \rho c}}\sqrt{t} \qquad (2.2\ b)$$

where, q = frictional heat flux

t – the time duration for heat flux application

k = thermal conductivity of the surface material

ρ = density

c = heat capacity

The frictional temperature rise for the pinion and gear at the start of contact, where the maximum sliding velocity and temperature rise occurs, can be determined by assuming two cylinders with radii corresponding to the radii of curvature of the teeth at

the contact point For two cylinders in contact as shown in figure 2-2, the durations of contact for pinion tooth and gear tooth are

$$t_P = b/V_P \text{ and } t_g = b/V_g \tag{2.3}$$

where b is the contact bandwidth as given by

$$b = \sqrt{\frac{16}{\pi} W_n R_e \left(\frac{1-\nu_p^2}{E_p} + \frac{1-\nu_g^2}{E_g}\right)} \tag{2.4}$$

and the surface velocities of pinion and gear can be calculated as

$$V_p = \omega_p R_p (1+M_g) x \sin\phi$$

$$V_g = \omega_p R_p \frac{(1+M_g)}{M_g} (1-x) \sin\phi \tag{2.5}$$

where R_e = the equivalent radius of curvature

x = the relative position along the line of action, measured from the pinion base circle

M_g= gear ratio

It is generally known that most gear surface failures are seen at the start of contact where the maximum temperature rise occurs due to the maximum heat generation Therefore in this study only the start of the contact point is considered.

The relative position of contact at the start of contact can be written as

$$x_s = 1 - \frac{\sqrt{\left(M_g + \frac{2}{N_p}\right)^2 - M_g^2 \cos^2\phi}}{(1+M_g)\sin\phi} \tag{2.6}$$

It can be assumed that the contact bandwidth and the velocities do not change during the traversal of the contact band at a particular position of contact because of the small changes in the relative position coordinate

The total heat flux, which depends on the work in overcoming friction and area generated inside the contact zone from the sliding contact of two teeth by friction, is defined as the energy generated per unit time due to friction,

$$q_t = fW_n V_s \qquad (2.7)$$

The heat flux generated per unit length will be

$$q = f\frac{W_n}{b}V_s \qquad (2.8)$$

where q = the frictional power intensity

f – coefficient of friction

W_n= the normal force per unit width on the surface

V_s = sliding velocity

b = width of contact band

The equation (2.2) can be applied for the start of contact in the pinion and gear by combining equations (2.2-2.8) as below in four groups of parameters

Material parameters $\phi_1(v, \rho, E, k, c)$

Geometric parameters $\phi_2(M_n, N_P, \phi, x_2)$

Lubrication and surface parameters $\phi_3(\psi, f, A_O/Ac)$

Application parameters $\phi_4(HP, \omega_P, C_d)$

$$\Delta T_P \equiv \phi_1(v, \rho, E, k, c)\times\phi_2(M_n, N_P, \phi, x_2)\times\phi_3(\psi, f, A_O/Ac)\times\phi_4(HP, \omega_P, C_d) \qquad (2.9)$$

$$\Delta T_p = \frac{1}{\pi^{3/4}} \left(\frac{1}{\left(\frac{1-\nu_p^2}{E_p} + \frac{1-\nu_g^2}{E_g} \right)^{3/4} \sqrt{k_p c}} \right) \left(\frac{\left[(1+M_g)^{3/4} \left[1-(M_g+1)x_2 \right] \sin^{3/4}\phi \right]}{M_g x_2^{3/4} (1-x_2)^{1/4} \cos^{3/4}\phi_p} \right) f \frac{Ac}{Ac} \left(\frac{HP^{3/4}}{n_p^{1/4} C_d^{1/2}} \right) \quad (2.9a)$$

$$\Delta T_g = \frac{1}{\pi^{3/4}} \left(\frac{1}{\left(\frac{1-\nu_p^2}{E_p} + \frac{1-\nu_g^2}{E_g} \right)^{3/4} \sqrt{k_g c}} \right) \left(\frac{\left[(1+M_g)^{3/4} \frac{1}{M_g} - (M_g+1)x_2 \right] \sin^{3/4}\phi}{M_g^{1} x_2^{3/4} (1-x_2)^{3/4} \cos^{3/4}\phi_g} \right) (1-\psi) f \frac{Ac}{Ac} \left(\frac{HP^{3/4}}{n_g^{1/4} C_d^{1/2}} \right) \quad (2.9b)$$

where ψ – heat partition of q to the pinion tooth surface

f = coefficient of friction between pinion gear surfaces

Ac/Ao – ratio of real area of contact to nominal area of contact

The lubricants and the surface roughness parameters ψ, f Ac/Ao are evaluated for each case in chapter 4. In this chapter they are assumed to be constant. For the practical range of oil film thickness and same pinion and gear material the heat partition for the pinion and gear is ψ=0.5 [27]

The temperature rise values for gear ratios Mg=2.5 and 10, center distance C_d=10,20 and 50 inches and different power between 10 to 100 Hp are calculated and given in tables 2.1-2.9 and plotted in figures 2.3-2.11.

It can be seen from the figures that the temperature rises are significantly increased for low numbers of teeth and high gear ratios. The decrease of center distance also increase the temperature rises. Therefore the temperature rise should be given serious consideration for low numbers of teeth and the high gear ratios.

Dimensionless Temperature Rise and The Thermal Stress

Dimensionless equations will be useful to compare the relative importance of the thermal effects to the mechanical effects. Dimensionless temperature rise equation is defined as below by using asperity flash temperature:

$$f_1(N_l, M_g) = \frac{\Delta T_p \sqrt{\rho k c}}{f\left(E_r \omega_p^{1/2} W_t^{3/2} C_d\right)^{1/4}} \qquad (2.10)$$

where, ΔT_p = instantaneous flash temperature as defined in equation (2.9).

ρ = gear material mass density

k = gear material's thermal conductivity,

c = gear material's specific heat density,

f – coefficient of friction,

E_r = modulus of elasticity,

ω_p = rotational speed,

W_t = tangential load per unit length of contact

C_d – center distance,

Dimensionless temperature rise values are calculated for center distances, C_d=20 in. gear ratios, M_g = 1, 2 4,10 and number of teeth ranging between 17 and 36 with Wt=1000 lb and ω_p =1800 rpm. The results are given in table 2-10 and plotted on figure 2-12. Thermal stress will be evaluated based on the maximum thermal gradient, which occurs during the mesh.

The thermal stress for fatigue attributed to the maximum instantaneous temperature rise can be calculated by using the equations given in reference [28]

$$\sigma_{th} = \frac{E_1 \alpha_1 \Delta T}{3(1-\nu_p)} \qquad (2.11)$$

where α_t = thermal expansion coefficient

ν_p = poisons ratio of pinion material

Eqnation (2 11) is used to calculate the tensile thermal stress at the asperity contact caused by the transient temperature rise induced by frictional or viscous heat inpnt In this chapter, only the frictional heat inpnt with a constant coefficant of friction is considered The change of the coefficient of friction and the viscous heat input when there is no metallic contact is analyzed in chapter 4

The considered examples are for gear ratio 1 2, 4 and 10 and center distance 20 inhes with Wt=1000 lb/in The results are given in table 2-11 and plotted in figure 2-13 It can be seen from the calculated results that the thermal stress increases with increasing gear ratio and decreases with increasing number of teeth

Dimensionless Contact Stress (Mechanical Stress)

The maximum Hertzian contact stress (σ_m) on gear tooth surface and the contact width (b) are given below with the assumption that Poisson s ratio is 0.3 [27]

$$\sigma_m = 0.591\sqrt{\frac{W_t \times E_{eq}}{R_{eq}}} \qquad (2.12)$$

$$b = 2.15\sqrt{\frac{W_t R_{eq}}{E_{eq}}} \qquad (2.13)$$

where $E_{eq} = \frac{E_1 E_2}{E_1 + E_2}$ and $R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$

The dimensionless nominal contact stress for the pinion can therefore be derived as a function of nnmber of pinion teeth and gear ratio as

$$f_2(N_p, M_g) = \frac{\sigma_m C_d^{0.5}}{E_1^{0.5} W_t^{0.5}} \qquad (2.14)$$

The results for mechanical contact stress and dimensionless mechanical stress are given in tables 2-12 and 2-13 and plotted in figures 2-12 and 2-13 for the same input values given in the previous example for calculation of thermal stress

The dimensionless ratio (nominal thermal stress / nominal mechanical stress) can be expressed as

$$f_3(N_p, M_g) = \frac{f_1(N_p, M_g)}{f_2(N_p, M_g)} \qquad (2\text{-}15)$$

The dimensionless stress ratios are calculated from the values of the dimensionless thermal stress ($f_1(N_p, M_g)$) given in table 2-10 and the mechanical stress ($f_2(N_p, M_g)$) given in table 2-13. The results which are given in table 2-14 show that the thermal stress can play an important role in surface failure and should not be ignored in performance evaluation of the gears

The following data are used for the performed calculation

Gear parameters

M_g = 1 2,4 10

C_d = 20 in.

Pinion rotational speed ω_p =1800 rpm

Tooth load W_t = 1000 lb/in

Material parameters

$E_{steel} = 30 \times 10^6$ psi

k_{steel} = 6 693 in-lb / in s-^{0}F

ρ_{steel} = 0 2#3 lb/ in^3

c_{steel} = 1035 in lb/lb-^{0}F

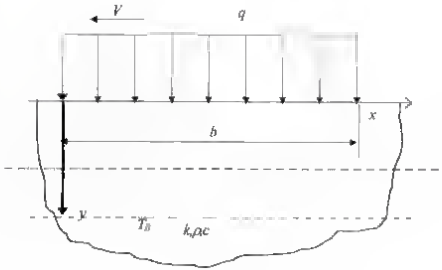


Figure 2-1 Moving band of heat sources on a semi-infinite solid

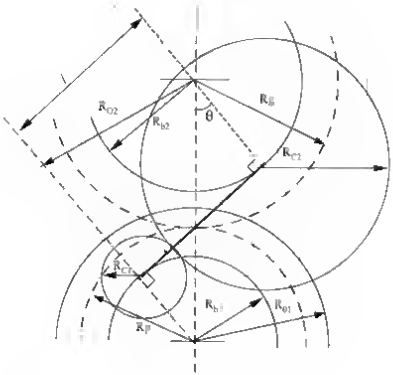


Figure 2-2 Radii of curvature of meshing tooth profiles

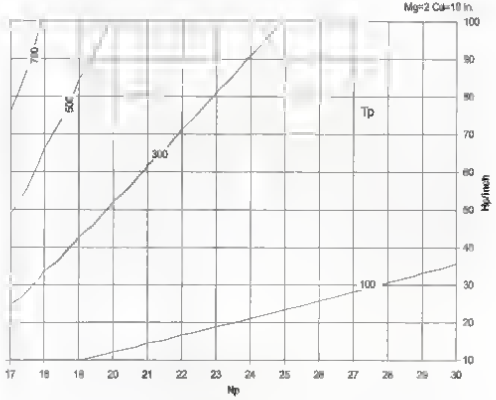


Figure 2-3 Temperature rise plot versus load and number of teeth for (C_d=10 in ; Mg=2)

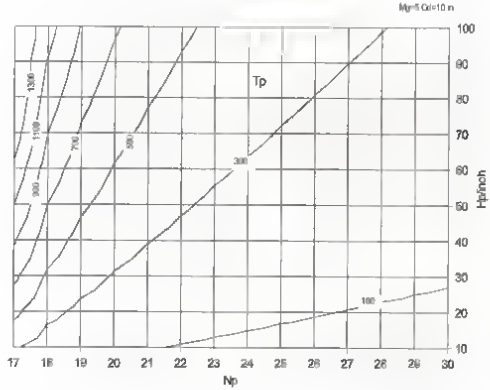


Figure 2-4 Temperature rise plot versus load and number of teeth for (C_d=10 m., Mg=5)

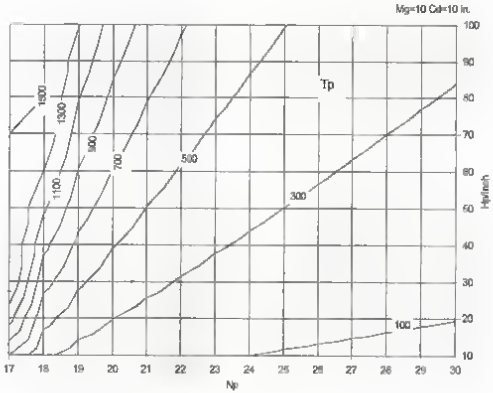


Figure 2-5 Temperature rise plot versus load and number of teeth for (C_d=10 in., Mg=10)

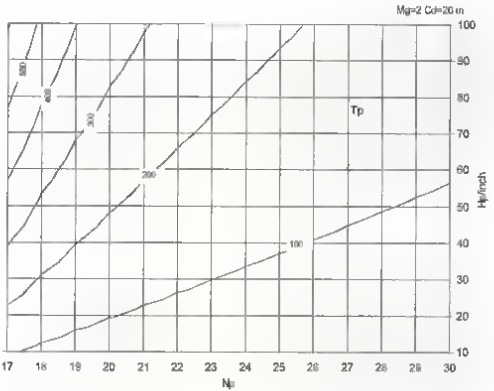


Figure 2.6 Temperature rise plot versus load and number of teeth for (C_d=20 in., Mg=2)

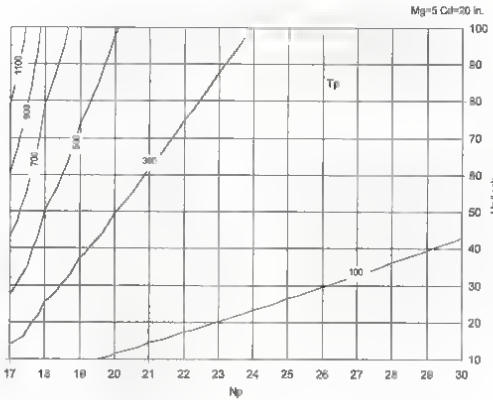


Figure 2.7 Temperature rise plot versus load and number of teeth for (C_d=20 in , Mg=5)

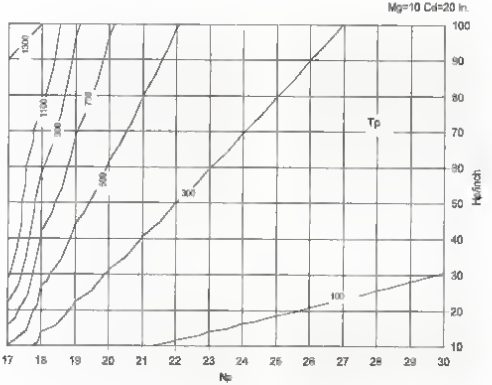


Figure 2-8 Temperature rise plot versus load and number of teeth for (C_d=20 in., Mg=10)

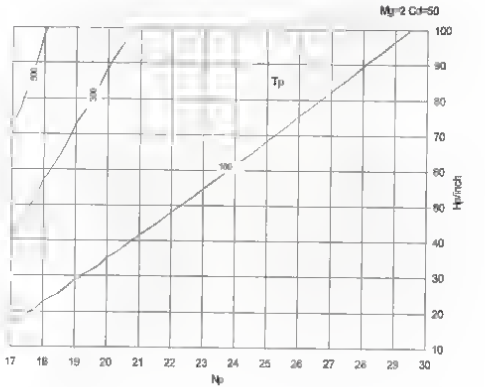


Figure 2-9 Temperature rise plot versus load and number of teeth for (C_d=50 in Mg=2)

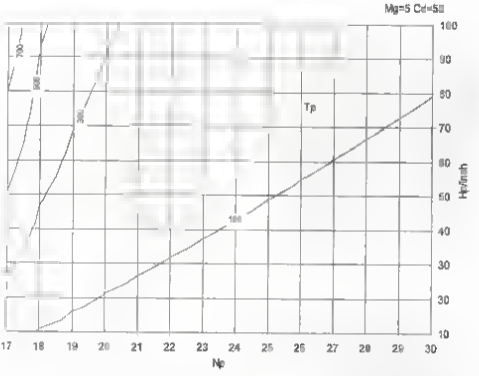


Figure 2-10 Temperature rise plot versus load and number of teeth for (C_d=50 in _Mg=5)

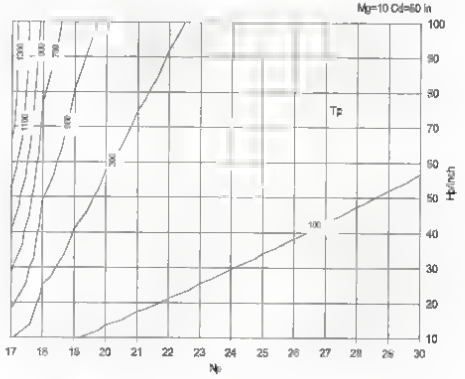


Figure 2.11 Temperature rise plot versus load and number of teeth for (C_d=50 in., M_g=10)

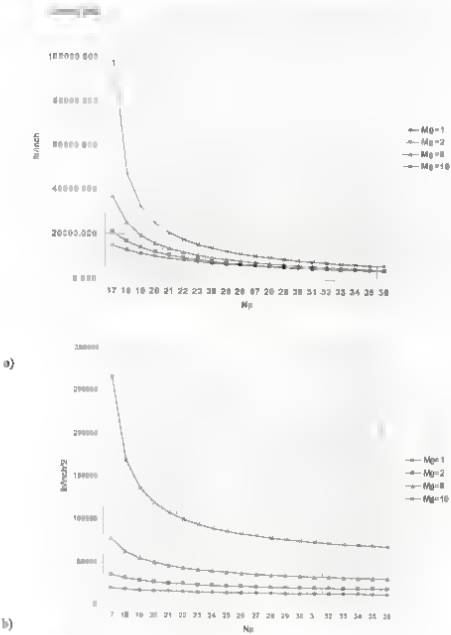
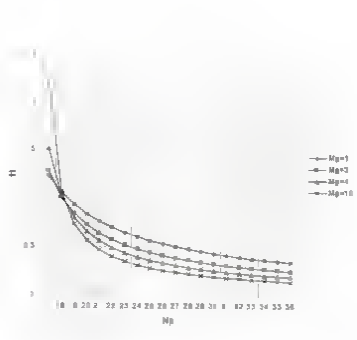


Figure 2.12 a) Nominal thermal stress and b) Mechanical contact stress plots versus gear ratios and number of teeth for (C_d=20 in., Load (W_t)=1000 lb)



a)

b)

Figure 2-13 a) Dimensionless thermal and b) Dimensionless mechanical stress plots versus gear ratios and number of teeth for (C_d=20 in., Load (W_t)=1000 lb.)

Table 2-1 Temperature rise values versus load and number of teeth for (C_d=10 in., Mg=2)

											Mg=1 Cd=[illegible]	
Np	yn		HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
18	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	434.8535	[illegible]	[illegible]
21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	285.4159	[illegible]	[illegible]	[illegible]
23	[illegible]	[illegible]	[illegible]	[illegible]	147.283	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24	[illegible]	[illegible]	11.21248	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	321.7284
25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
26	4.1384	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
27	[illegible]	[illegible]	[illegible]	77.34935	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
29	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	175.483	[illegible]	224.574	[illegible]
30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 2-2 Temperature rise values versus load and number of teeth for (C_d=10 in., Mg=5)

										Cd=[illegible] Mg=5		
Np	[illegible]		HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
18	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	380.5155	[illegible]	[illegible]	544.2325	[illegible]	[illegible]	[illegible]
21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
22	[illegible]	[illegible]	[illegible]	157.1173	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
23	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	324.0577	[illegible]	[illegible]
26	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
29	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	221.6092	[illegible]	[illegible]

Table 2-3 Temperature rise values versus load and number of teeth for (C$_d$=10 in Mg=10)

			Cd=10 Mg= [illegible]									
Np	x0		HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
11	0 0038	[illegible]	[illegible]	1108 777	[illegible]	1094 231	[illegible]	2702 9[illegible]	3084 [illegible]	3353 [illegible]	[illegible]	3844 [illegible]
[illegible]	[illegible]	[illegible]	337 [illegible]	567 [illegible]	768 7781	[illegible]	[illegible]	1204 [illegible]	1453 273	1808 134	[illegible]	[illegible]
14	[illegible]	[illegible]	[illegible] 5831	181 032	128 8874	[illegible]	777 4[illegible]	[illegible] 3571	[illegible]	[illegible] 077	[illegible]	[illegible] 401
[illegible]	[illegible]	4 567225783	[illegible]	108 2588	[illegible]	[illegible]	802 8324	[illegible] 2600	770 3004	651 1458	[illegible] 0442	[illegible] 007
[illegible]	[illegible] 184	[illegible]	[illegible] 1110	241 1425	330 1550	420 [illegible]	[illegible]	[illegible]	435 [illegible]	108 4818	11 [illegible] 1406	835 [illegible]
22	[illegible] 225	0 358808164	128 [illegible]	111 3[illegible]	208 2200	358 811	424 1 402	408 4162	546 432	683 3684	[illegible] 28	[illegible]
[illegible]	0 0264	[illegible]	[illegible] 5306	[illegible] 6311	153 231[illegible]	[illegible]	311 411[illegible]	475 [illegible]	41[illegible] 0100	638 4385	177 2432	824 1078
14	[illegible]	0 278493528	[illegible] 8841	59 1451	225 6811	[illegible] 921	331 0611	179 5496	[illegible]	470 6414	1[illegible] 4421	158 1432
25	[illegible]	[illegible] 543352	[illegible] 4211 1	50 1[illegible]	283 841	262 [illegible]	[illegible]	342 [illegible]	384 8364	425 1131	[illegible]	502 [illegible]
26	[illegible]	[illegible]	41 [illegible]	127 2728	[illegible]	238 8843	272 8225	311 [illegible] 42	35[illegible] 2654	[illegible]	[illegible] 141	458 [illegible]
11	[illegible] 0341	0 11[illegible] 382231	10 13518	126 [illegible]	[illegible] 2725	[illegible]	[illegible]	[illegible]	321 34[illegible]	157 4079	[illegible]	422 [illegible]
28	[illegible]	[illegible]	[illegible] 84811	111 [illegible] 131	[illegible]	[illegible] 9841	137 [illegible]	281 [illegible] 72	299 [illegible]	111 2041	[illegible] 5011	391 [illegible]
[illegible]	[illegible]	0 152672[illegible]	64 93[illegible]	1081 1[illegible]	148 [illegible]	[illegible] 0778	[illegible]	[illegible]	279 41[illegible]	[illegible] 9083	331 4314	[illegible]
[illegible]	0 0403	0 11173128	[illegible]	102 34[illegible]	1081 132	72 [illegible]	[illegible]	[illegible]	281 [illegible]	[illegible] 4830	[illegible] 1078	[illegible] 1078

Table 2-4 Temperature rise values versus load and number of teeth for (C$_d$=20 in Mg=2)

			Mg=2 Cd=20									
Np	x0		P=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
11	0 046970	0 42[illegible]	108 3670	[illegible]	[illegible] 2002	305 6046	36[illegible] 2788	814 1174	[illegible]	513 [illegible] 37	561 4311	607.5[illegible]
[illegible]	0 002782	0 34[illegible]	45 [illegible] 037	181 7737	[illegible] 13	34[illegible] 7878	285 [illegible]	327 73[illegible]	381 [illegible] 7	406 6535	444 2100	[illegible]
[illegible]	0 075363	0 2837[illegible] 1	[illegible] 3108	110 [illegible] 36	181 572	201 7204	228 4682	273 4[illegible] 24	300 8222	339.2518	370 584	401 6857
[illegible]	[illegible]	0 244821	81 4828	103 4[illegible]	14[illegible] 126	113 9273	[illegible]	231 [illegible]	284 8341	282 5008	[illegible] 5248	345 7008
21	0 087254	0 1[illegible] 1779	54 22811	81 20222	121[illegible]	[illegible]	[illegible]	201 [illegible]	111 176	267 [illegible]	[illegible] 183	[illegible]
22	0 10884	0 183385	48[illegible] 509	81 78861	118[illegible] 84	11 5041	42 5541	[illegible] 37	208 1158	231 2338	111 [illegible]	273 3827
[illegible]	0 115885	0 11 5554	44 [illegible] 3821	141[illegible]	[illegible] 5852	14[illegible] 92	41 5584	[illegible]	108 [illegible] 153	209.08	[illegible]	248 1008
24	[illegible]	0 [illegible] 60835	40 45534	[illegible]	92 11822	[illegible] 4 428	35 2708	11 [illegible]	114 [illegible]	92 43[illegible]	[illegible]	[illegible] 4871
[illegible]	0 13 314	[illegible]	11 38211	82 [illegible] 7094	45 11424	65 1344	24 [illegible]	143 3127	1[illegible] 0773	177 [illegible]	94 2481	[illegible] 3100
[illegible]	0 [illegible] 10300	0 138324	34 77[illegible] 1	58 47[illegible] 2	79 26142	[illegible]	[illegible] 2845	133 3813	140 [illegible]	108 4811	[illegible] 577	81 5334
27	0 [illegible] 494	0 1293[illegible] 3	3[illegible] 12108	54 [illegible]	14 13275	9[illegible] 8844	130 1418	114 0718	139.0584	154 [illegible]	[illegible]	[illegible] 0012
28	0 [illegible] 11065	0 [illegible] 1111	30 56065	1[illegible]	69 [illegible] 322	88 43867	10[illegible] 457	111 [illegible] 581	131 1182	148 3118	108 7878	111 8552
29	0 10678	0 [illegible] 14788	[illegible]	48 [illegible]	88 72878	[illegible] 56735	88 41581	110 5430	124 0883	131 1830	14[illegible] 6015	182 [illegible] 118
30	0 102108	[illegible] 506 18	27 3006	45 [illegible] 01	82.23874	77.26825	91 [illegible]	84 6727	1[illegible] 7 0815	120 [illegible]	41 8737	153 [illegible]

Table 2-5 Temperature rise values versus load and number of teeth for (C_d=20 in Mg-5)

No			HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
10												
11												
12												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												

Table 2-6 Temperature rise values versus load and number of teeth for (C_d=20 in Mg-10)

No			HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
10												
11												
12												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												

Table 2.7 Temperature rise values versus load and number of teeth for (C_d=50 in. Mg=2)

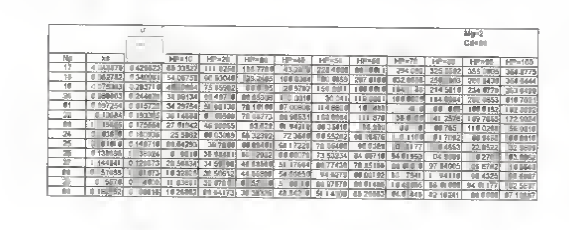


Table 2.8 Temperature rise values versus load and number of teeth for (C_d=50 in , Mg=5)

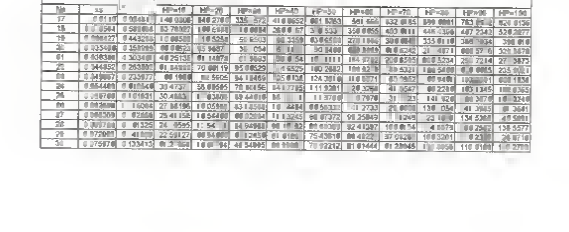


Table 2.9 Temperature rise values versus load and number of teeth for (C_e=50 in., Mg=10)

Np	ωb	HP=11	HP=20	HP=30	HP=40	HP=60	HP=80	HP=70	HP=90	HP=100	HP=120
17	0.003195	0.98330	310.3150	1099.2998	718.7885	93.8472	1954.381	1000.813	1358.966	1466.962	1838.428	1773.11
18	0.007661	0.94461	91.6218	353.0690	344.2545	827.581	934.9767	818.9988	648.9235	718.3638	784.1388	843.2662
19	0.012088	0.91540	37.8786	178.1784	251.1986	294.1957	341.8732	399.118	441.8736	498.8801	540.2888	584.2963
20	0.016622	0.89228	19.8419	135.9215	183.8815	328.8373	268.5796	267.1872	343.0421	361.5864	414.8231	453.8778
21	0.021255	0.87182	11.4256	81.7891	138.4663	91.8680	222.0855	264.8343	288.8439	318.9628	345.1536	372.8113
22	0.025959	0.85567	7.5185	66.4239	129.8453	89.4984	188.7395	218.5316	244.1899	281.8154	294.8434	317.1979
23	0.030529	0.84261	4.9681	53.9534	111.2436	85.8186	86.1178	91.4897	213.1038	236.2248	258.1183	276.8778
24	0.035043	0.83184	44.2761	14.4481	100.9218	35.2201	148.9465	69.1197	196.6432	217.1412	229.3057	248.9818
25	0.039189	0.82284	39.9188	0.2978	91.1805	0.9	201.1169	53.8181	172.7341	190.2327	203.8618	224.1887
26	0.043151	0.82296	36.5928	0.0364	83.2852	0.0	181.2541	139.8385	151.1801	113.6818	89.8744	206.2296
27	0.047251	0.82352	33.8018	0.0151	76.7359	0.0	164.6408	0.21642	133.8178	148.8662	159.8377	176.5867
28	0.050884	0.82418	31.4759	0.0038	71.1801	0.0	150.8659	134.1815	89.4055	94.6442	98.1831	116.8478
29	0.054825	0.82572	29.5429	0.0000	66.2852	0.0	138.9227	0.1729	84.9809	89.8148	93.2963	108.3984
30	0.058329	0.82718	27.8738	0.0000	62.0344	0.0	128.6274	0.1654	81.0356	85.6807	88.9829	103.3984

Table 2.10 Dimensionless temperature rise values versus gear ratios and number of teeth for (C_e=20 in., load (W_t) =1000 lb)

	f1 (Np Mg)			
Np	Mg=1	Mg=2	Mg=4	Mg=10
17	1.2341327	1.2608878	1.5753222	2.2240728
18	1.0825424	1.1131860	1.0332812	1.6884653
19	0.9387405	0.9452264	0.7885413	0.7335853
20	0.8408458	0.7296030	0.6587437	0.5776508
21	0.7631012	0.6427182	0.5607148	0.4687411
22	0.7022259	0.5781607	0.4908863	0.4012348
23	0.6477503	0.5230206	0.4375112	0.3513548
24	0.6032255	0.4794722	0.3952733	0.3131285
25	0.5648828	0.4436562	0.3608614	0.2828276
26	0.5315082	0.4121058	0.3329584	0.2586542
27	0.5021388	0.385544	0.3082117	0.2378378
28	0.4760621	0.3622015	0.2874803	0.2202818
29	0.4527515	0.3417503	0.2685184	0.2053908
30	0.4317882	0.3238983	0.2537484	0.1924826
31	0.4127988	0.3073704	0.2397852	0.1811237
32	0.3954744	0.2927852	0.2273548	0.171692
33	0.3795583	0.2785453	0.2161073	0.1621468
34	0.3651323	0.2675173	0.2061832	0.1541224
35	0.3517366	0.258523	0.1968484	0.1468758
36	0.3393483	0.2484312	0.1885674	0.1402898

Table 2-11 Nominal thermal stress values for temperature rise values versus gear ratios and number of teeth for (C_d=20 in., load (W_t) = 1000 lb)

Nominal Thermal stress (lbf/in^2)				
Np	Mg=1	Mg=2	Mg=4	Mg=10
17	15131 497	21266 652	30938 564	86195 493
18	13027 659	18037 715	25188 207	47031 088
19	11485 22	14048 812	18465 607	32390 67
20	10266 602	12111 526	16008 246	25113 212
21	9350 257	10680 824	13088 378	20664 769
22	8598 3532	9575 1858	11665 703	17870 76
23	7942 0578	8661 6558	10885 052	16471 761
24	7368 046	7885 6477	9835 4801	13708 483
25	6920 0572	7302 8734	8787 8837	12454 141
26	6510 8477	6648 5244	8161 603	11367 71
27	6156 5431	6405 3857	7813 1856	10464 242
28	5836 6183	6019 166	7008 2658	8689 875
29	5581 1106	5870 3342	6588 9898	8644 2023
30	5293 8388	5377 9941	6165 5503	8474 8676
31	5060 887	5107 9648	5845 4164	7878 974
32	4846 8481	4885 2666	5542 1983	7533 9337
33	4654 9275	4645 9872	5266 6354	7140 1237
34	4478 8285	4445 7022	5024 1166	6788 6854
35	4312 8207	4282 6943	4800 852G	6487 5887
36	4163 683	4008 2858	4687 3833	6177 6658

Table 2-12 Dimensionless mechanical stress values versus gear ratios and number of teeth for (C_d=20 in., load (W_t)=1000 lb)

f2(Np, Mg)				
Np	Mg=1	Mg=2	Mg=4	Mg=10
17	1 6317009	2 4181161	4 0516181	6 2613614
18	1 5344637	2 1483046	3 2817524	5 6031643
19	1 4626077	1 9750677	2 8462184	4 7723789
20	1 4000014	1 851638	2 5678486	4 1001479
21	1 3448822	1 7596128	2 4062422	3 7046015
22	1 3263335	1 687888	2 2717554	3 8185778
23	1 3002338	1 6302122	2 1676235	3 3144098
24	1 2758108	1 5626390	2 0843758	3 1888461
25	1 2558428	1 5434147	2 0181062	3 0928332
29	1 2371888	1 5048028	1 9581839	2 9283203
27	1 2216888	1 4610178	1 9108128	2 8428183
28	1 20812	1 4556508	1 8892867	2 7881737
29	1 1881089	1 4336838	1 8330228	2 7858582
30	1 1855452	1 4146221	1 8012473	2 6502789
31	1 1788728	1 3672881	1 7731123	2 8818307
32	1 1675745	1 3616618	1 7488161	2 5582788
33	1 1588149	1 3877078	1 7254848	2 5188173
34	1 1528618	1 3598411	1 78818	2 4846482
35	1 1488812	1 3435148	1 666788	2 4834838
36	1 1488384	1 3328825	1 8888888	2 4248188

Table 2.13 Nominal mechanical contact stress values for temperature rise values versus gear ratios and number of teeth for (C_d=20 in , Load (W_t)=1000 lb)

Nominal Mechanical Stress (lb/in^2)				
Np	Mg=1	Mg=2	Mg=4	Mg=10
17	100[illegible]5 275	30271 706	79405 070	2065[illegible] 61
18	10703 51	32240 772	83103 170	1[illegible]
19	17016 007	29826 406	85155 532	137078 17
20	17244 425	27777 57	80109 010	119740 85
21	10712 203	28304 197	46500 670	1[illegible]713 02
22	102[illegible] 043	25317 08	43902 354	1[illegible]071 54
23	16824 540	24463 103	41975 040	85190 003
24	15626 427	23744 084	40363 760	[illegible]707 [illegible]
26	19371 074	23151 221	3[illegible]42 029	97102 [illegible]
26	15152 370	22647 043	37939 420	84130 404
27	14862 543	22215 269	37002 733	81053 700
28	14748 307	21830 263	36187 07	79538 458
29	14649 900	21509 458	35406 334	77714 117
30	14510 805	21217 831	34881 605	76123 302
31	14403 [illegible]	20950 122	34336 172	74723 281
32	14299 [illegible]	20725 378	33090 244	73480 [illegible]
33	14206 [illegible]	20519 619	33414 [illegible]	72370 [illegible]
34	14121 083	20325 010	33020 281	71371 858
35	1[illegible]3 81444	20132 72117	32[illegible]2 8444	74[illegible] [illegible]377
36	13873 [illegible]74	14[illegible] 73881	12337 21881	4448[illegible]7 44334

CHAPTER 3
DIMENSIONLESS RELATIONSHIP FOR CONTACT STRESS MODIFICATION

Thermal Stress

Thermal stress is the stress arising from non uniform temperature distribution. When the material is subjected to a temperature gradient, the material tends to extend more on the higher temperature and less on the lower temperature side of the temperature gradient [29] Thermal deformation simply means that as the "thermal" energy (and temperature) of a material increases, so does the vibration of its atoms and molecules, and this increased vibration results in what can be considered a stretching of the molecular bonds which causes the material to expand A system of thermal strains and thermal stresses may be introduced which are dependent on the shape of body and the temperature distribution

The thermal stress equation as given in equation (2 11) and rewritten below is depend on material parameters such as modulus of elasticity (E) thermal expansion coefficient (α_t), poisson s ratio (ν) and the temperature gradient (ΔT)

$$\sigma_{th} = \frac{E_t \alpha_t \Delta T}{3(1-\nu_p)} \tag{3 1}$$

A linear relationship between the stress and strain within the elastic region is given by Hooke s law and represented by equation (3 2) as

$$\sigma_{th} = \varepsilon E \tag{3 2}$$

where, ε = thermal strain.

Thermal fatigue

Although brittle materials may fail in one cycle of thermal stress application, ductile materials may require one or more cycle of thermal stress before fracture is generated. Failure under repetitive application of thermal stress is called *thermal stress fatigue*. Thermal fatigue is defined as the gradual deterioration and eventual cracking of material by alternate heating and cooling when free thermal expansion is partially or totally constrained [29].

The experimental studies showed that for the same plastic strain range, the number of cycles to failure were much less for thermally cycled specimens than mechanically cycled specimens [29,30].

Low-Cycle Fatigue and High-Cycle Fatigue

Fatigue failure investigation over the years has led to the observation that the fatigue process actually consists of two domains of cyclic stressing or straining. One of the failures occurs as significant amounts of plastic strain resulted from high cyclic load and low number of cycles. This domain commonly referred to as *low-cycle fatigue*. The other type is that the strain stays in the elastic range with low cyclic load and high number of cycle, which is referred to as *high-cycle fatigue*. The high-cycle fatigue range generally is defined as failure in 50000 cycles or above [31].

Generally, low-cycle thermal fatigue failures under high temperatures are observed as intercrystalline cracks and high cycle fatigue with moderate temperature cycling are observed as transcrystalline cracks. For transcrystalline failure, fatigue cracks propagate through grains along slip bands on crystallographic planes. On the other hand,

intercrystalline cracking refers to separation along the boundaries between grains as a result of rotation and movement of the entire grain [32]

Thermal Shock

When the thermal stress is generated by sudden changes in temperature, the process is referred to as thermal shock The stresses induced in thermal-shock are often greater than those due to slow heating and cooling The materials may be embrittled by rapid application of stress and therefore may not be able to withstand the thermal-shock [29] Thermal shock stress is characterized as a severe stress field generated in a structure by sudden application of a large heat flux, which increases the surface temperature instantaneously [33]

The thermal shock resistance of brittle materials is determined by the temperature rise that will cause failure in one load-cycle The maximum shock temperature for failure to occur using the single cycle criterion is

$$T_{max} \propto \frac{k\sigma_{max}}{E\alpha} \qquad (3.3\text{-a})$$

for low value of Biot's modules (β) (*mild shock*), and

$$T_{max} \propto \frac{\sigma_f}{E\alpha} \qquad (3.3\text{-b})$$

for high values of β (*severe shock*),

where σ_{max} – the maximum stress

σ_f – the breaking stress (fracture stress)

α – thermal expansion coefficient

E – modulus of elasticity

($\beta = a H / k$) is the Biot s modulus, a dimensionless heat transfer parameter, that depends on the emissivity H, thermal conductivity k, and the characteristic size of the body a. The implication of (3 3-a) and (3 3 b) is that for large β the conductivity does not influence the temperature that can be tolerated without failure.

For ductile materials, failure occurs with multiple-cycles rather than being caused by a single application of load. The failure of ductile materials due to repeated thermal shock loading is given as [29]

$$N_f = G\left(\alpha\left(\Delta T_0\right) - 2\varepsilon_e\right)^d \qquad (3\ 4)$$

where G and d are constants

α = the thermal expansion coefficient, / °F

ΔT_0 = change in temperature, °F

ε_e = the elastic limit of the material psi

Endurance Limit

Most metals follow the characteristic pattern of failure occurring at an increasingly larger number of flexing cycles when the stress is reduced. The endurance limit is the highest stress at which material can be subjected to repeated stress without failure. This value is obtained from a stress-number of cycle (S/N) diagram. Ferrous metals usually exhibit a characteristic knee in their plots, as shown in figure 3 1 and the endurance limit is the asymptote [34]. Moreover, some materials do not have well-defined knees. In this case usually, the fatigue limit at a high cyclic life ($>10^6$cycles) will also be called the endurance limit.

Combined Thermal and Mechanical Stress Effects on Fatigue

Thermal stress cycling coupled with the mechanical stresses developed in the asperity contact interaction cause cracks to appear early in the life of rolling-sliding contact elements [29]

Experimental studies for investigating the repeated thermal shock stress effects on bending fatigue of two types of high-carbon (4340-4350) and low-carbon (1020) steels are reported in reference [27] The tests were done to identical specimens with and without thermal shock application. The results of the tests are given in figures 3-2 to 3-3

The results prove that high-carbon steel endurance limit is decreased 45% with 40 thermal cycles For 1020 low-carbon steel endurance limit is also decreased but only 12%

The above study shows the material life is dependent on the combined mechanical and thermal stresses when the component is under application of both loads [27] Therefore, the following design criterion is applied to this study

$$1 = \sqrt{\left(\frac{\sigma_m}{K_m \sigma_u}\right)^2 + \left(\frac{\sigma_t}{K_t \sigma_u}\right)^2} \qquad (3.5)$$

where σ_m = the mechanical tensile stress on the surface

σ_t = the thermal tensile stress on the surface

σ_u = the ultimate tensile strength

K_m = the ratio of the fatigue limit due to mechanical loading to the ultimate tensile strength

K_t = the ratio of the thermal fatigue limit to the ultimate tensile strength

K_m and K_t are calculated for high-carbon 4340 steels and 1020 low carbon steel by using the experimental data from figures 3-2 and 3 3 and equation (3.5) The values are given in table 3-1

Modification of Mechanical Stress Combined with Thermal Stress

In this section a modification factor, which shows the influence of thermal stress, is proposed Equation (3 5) can be rewritten in the form of stress ratios as below

$$1=\left(\frac{\sigma_m}{K_m\sigma_u}\right)\sqrt{1+K} \qquad (3\ 6)$$

where $K=\left(\frac{K_m\sigma_t}{K_t\sigma_m}\right)^2$ is the stress modification factor which can be expanded by combining equations (2 9a) (2 11) and (2 12) grouping the result as geometric factors, material factors, lubrication factors and application factors as given below

$$K=\left[\frac{(1-x_s)^{1/2}(1+M_g)^{\,2}\left[1-\left(M_g\ \text{[illegible]}\right)x\right]^2}{M_g^{\,2}\ \text{[illegible]}}\right]\left(\frac{\sin^{3/4}\varphi}{3\,\text{[illegible]}\cos^{3/4}\varphi}\right)\left[\left(\frac{K_m}{K_t}\right)\frac{\text{[illegible]}}{\text{[illegible]}\left(\frac{\text{[illegible]}^2}{E_p}\ \text{[illegible]}\ \frac{\text{[illegible]}^2}{E_g}\right)^{1/2}}\right]\left[\psi_p f\frac{An}{Ac}\right]^2\left[\text{[illegible]}\right] \qquad (3\ 7)$$

where x_s is relative position of the starting point of contact (along the line of action)

M_g = gear ratio (N_g/N_p)

φ = pressure angle

E_p, E_g and E_e are elasticity of modulus of pinion gear and equivalent respectively

ψ_p = heat transfer partition of coefficient

f = coefficient of friction

Io Ac are nominal and real area of contact

C_d – Center distance

ω_p = angular velocity of pinion

HP – applied load (horse power)

The modification factors (K) and $\frac{1}{\sqrt{1+K}} = \left(\frac{\sigma_m}{K_m \sigma_x}\right)$ are evaluated for gear ratios 2 5 and 10 center distance 10 20 and 50 in and load 10 to 100 Hp for the following data and conditions

Steel data

E_{steel} – 30 kpsi, $\alpha_{steel} = 9.61 \times 10^{-6}$ in/in ^{0}F

$k_{steel} = 6.693$ in-lb/in s-^{0}F $\rho_{steel} = 0.283$ lb / in^3, $c_{steel} = 1035$ in lb/ lb-^{0}F

Gear materials

4340 *high-carbon* steel and 1020 *low-carbon* steel,

Ultimate strength of materials

Two cases are considered for determining the allowable ultimate stress

In the first case the temperature effect on reducing the ultimate stress is not considered and the values used this case are

σ_u *(4340 high-carbon steel)* –186x10^3 psi.

σ_u *(1020 low carbon steel)* = 100x10^3 psi

In the second case ultimate strength is considered to be effected by the temperature rise The values of the ultimate strength in this case are given by figure 3-5

Pinion rotational speed (ω_p) – 180 rad/sec, pressure angle (ψ) = 20^0 heat partition coefficient, (α) = 0 5 and the coefficient of friction (f) = 0 05 are used in the calculations.

The results are given in tables 3-2 to 3-10 and plotted in figures 3-6 to 3-14 for the first case. The values show that the allowable mechanical stress is decreased with lower number of teeth, higher load and higher gear ratio as a result of the imposed thermal stress

The next study in this research deals with the effect of the ultimate strength change with temperature. Therefore the ultimate strengths of the materials (4340 high-carbon steel and 1020 low-carbon steel) are modified for the temperatures as given in chapter 2

Accordingly, the modification parameters can be expressed as

$$\frac{\sigma_{ur}}{\sqrt{1+K}} - \left(\frac{\sigma_u}{K_u \sigma_u}\right) \qquad (3\ 8)$$

where σ_{ur} = ultimate strength at the specific temperature

σ_u = ultimate strength at room temperature (without temperature change consideration).

The result given in tables 3-11 to 3-12 and plotted in figures 3-15 to 3-23 shows that with the higher temperature the allowable mechanical stress decreases further as a result of the decrease in ultimate strength

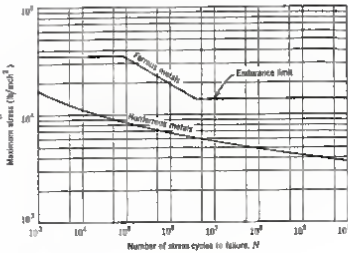


Figure 3.1 Typical endurance stress curve (S N)

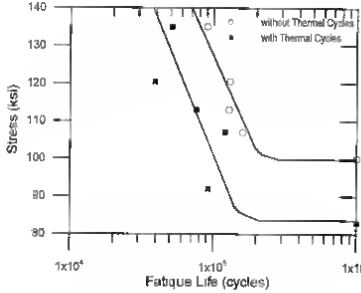


Figure 3-2 Fatigue data for 4340 steel (High carbon) [27]

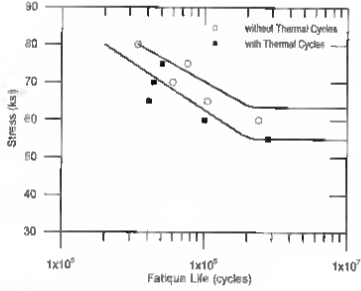


Figure 3.3 Fatigue data for 1020 low carbon steel [27]

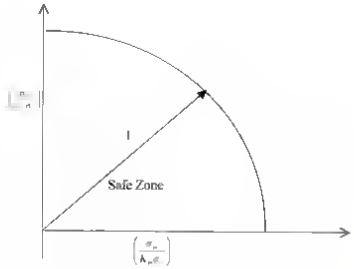


Figure 3-4 Design approach plot

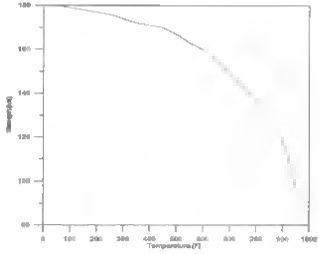


Figure 3-5 Ultimate strength change versus temperature rise

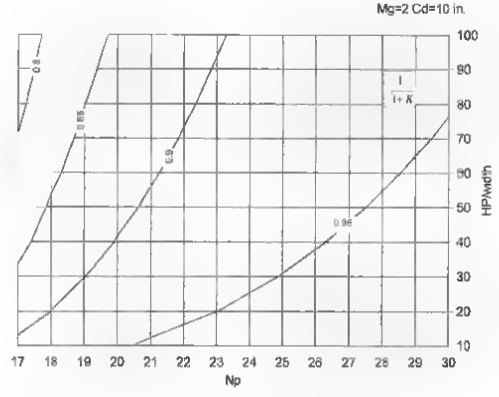


Figure 3-6 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=10in. M_g=2)

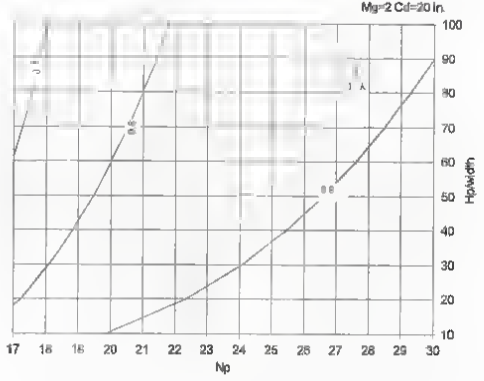


Figure 3-7 Design factor $1/\sqrt{(1+K_j)}$ versus load and number of teeth for (C_d=20in., M_g=2)

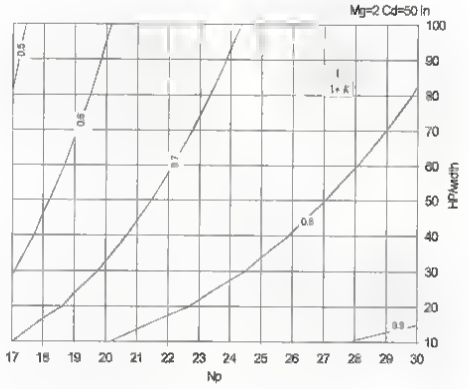


Figure 3-8 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=50in M_g=2)

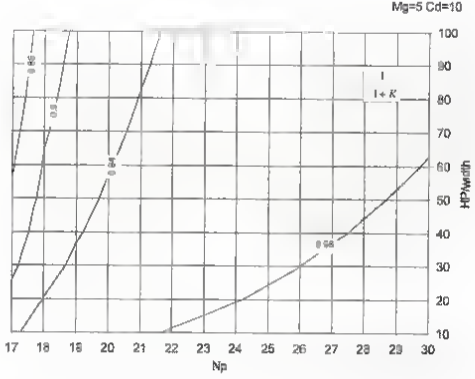


Figure 3.9 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=10in., M_g=5)

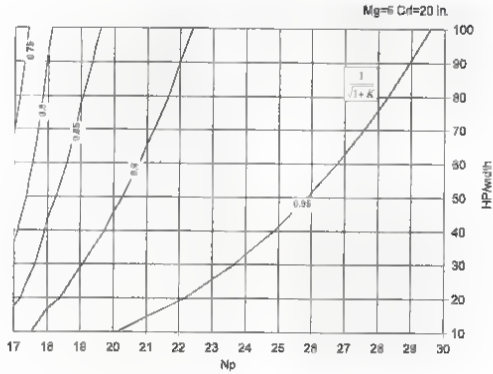


Figure 3-10 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=20in Mg=5)

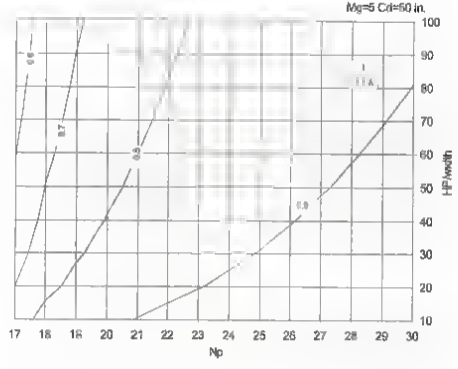


Figure 3-11 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=50in., Mg=5)

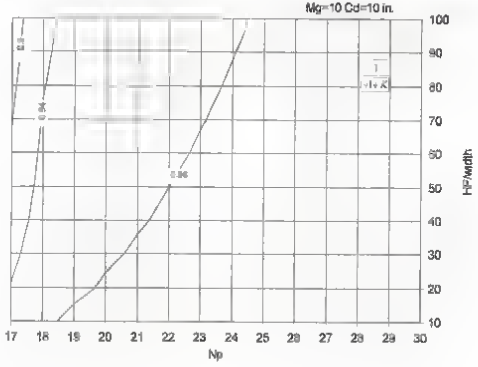


Figure 3-12 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=10in., Mg=10)

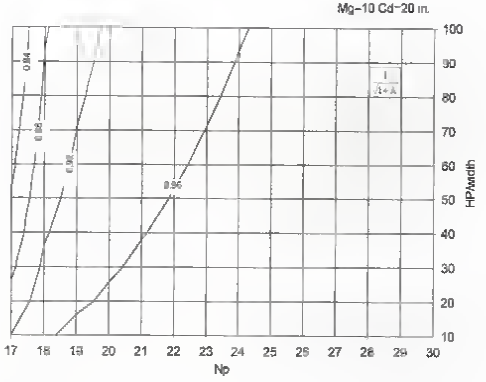


Figure 3-13 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=20in Mg=10)

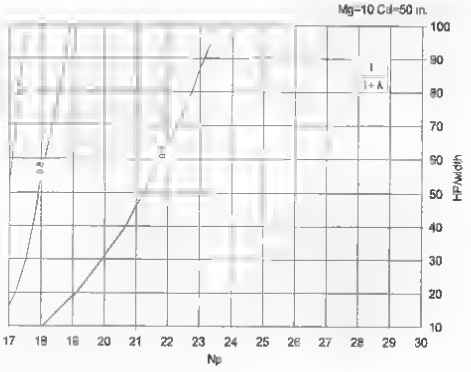


Figure 3.14 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=50in Mg=5)

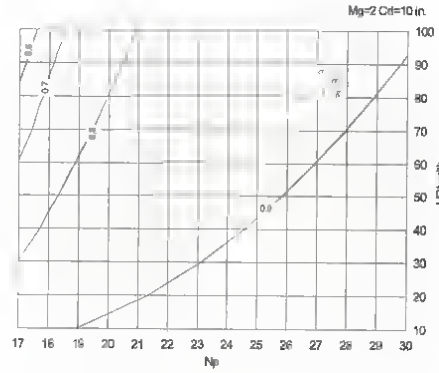


Figure 3-15 Design factor $\frac{(\sigma_{ac}/\sigma_{at})}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=10 in , Mg=2)

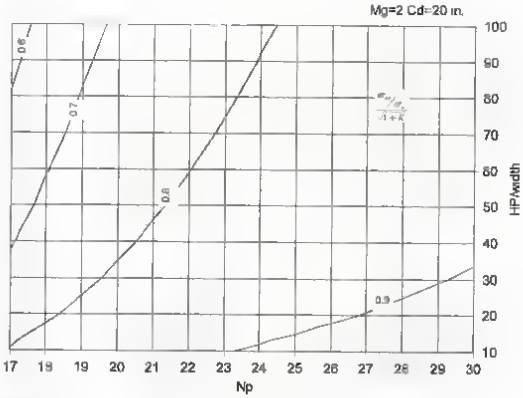


Figure 3.16 Design factor $\frac{(\sigma_w,\ \sigma_s)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=20 in., Mg=2)

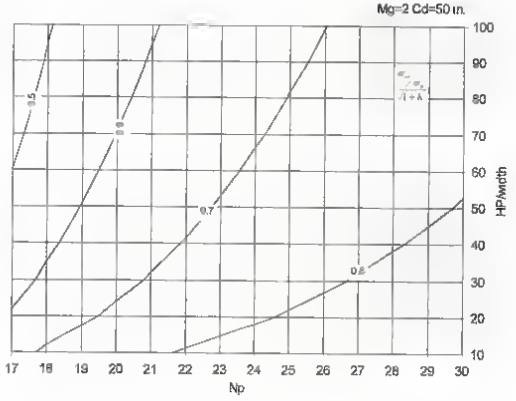


Figure 3.17 Design factor $\frac{f(\sigma_w, \sigma_c)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=50 in., Mg=2)

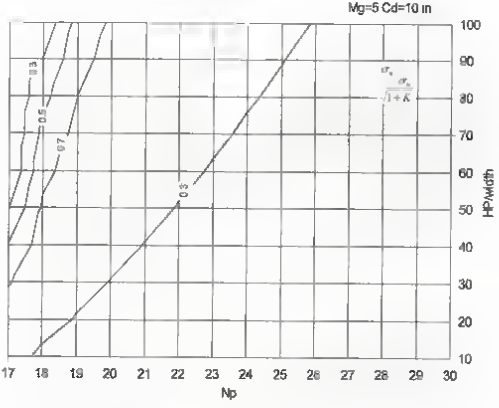


Figure 3-18 Design factor $\frac{(\sigma_w \sigma_i)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=10 in., Mg=5)

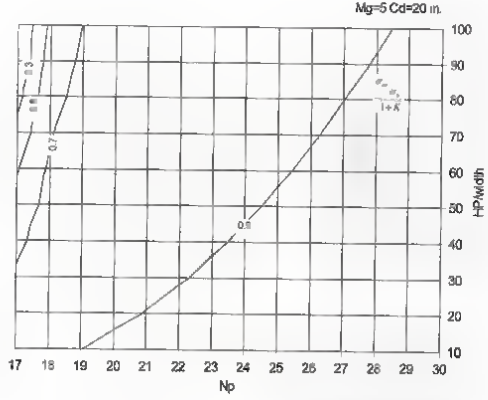


Figure 3-19 Design factor $\frac{(\sigma_w/\sigma_t)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=20 in Mg=5)

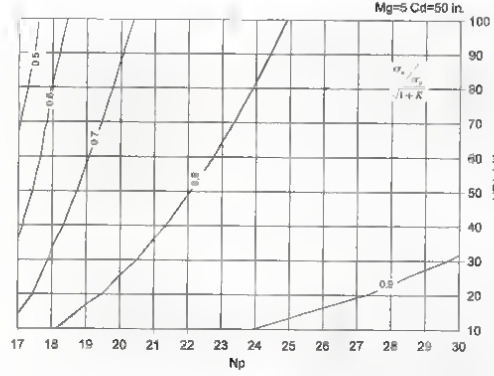


Figure 3-20 Design factor $\frac{(\sigma_w/\sigma_c)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=50 in – Mg=5)

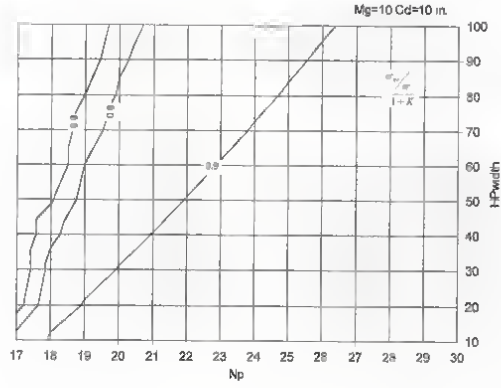


Figure 3-21 Design factor $\frac{(\sigma_w/\sigma_c)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=10 in., Mg=10)

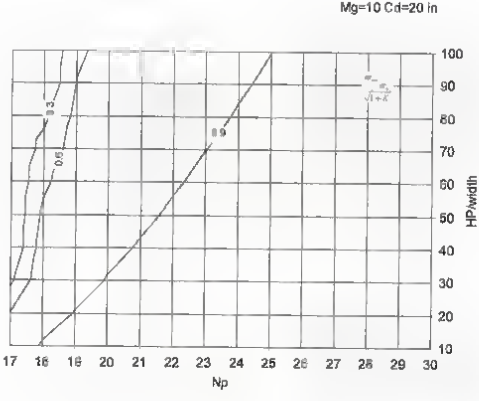


Figure 3-22 Design factor $\frac{(\sigma_w \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=20 in., Mg=10)

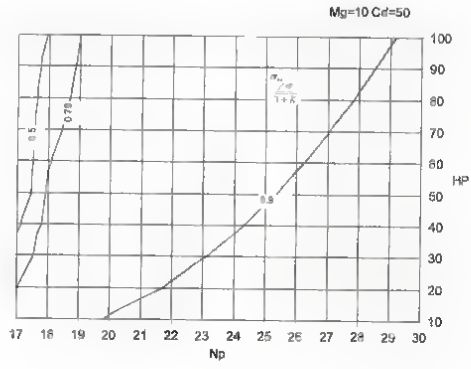


Figure 3-23 Design factor $\frac{(\sigma_w \sigma_f)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=50 in., Mg=10)

Table 3-1 Factors K_T, K_M for combined mechanical and thermal fatigue for 4340 high carbon steel and 1020 low carbon steel

4340 High carbon steel

ΔT 300 F	$(\sigma_T) = 41$ ksi
$\alpha = 9.61$ in/in-F	$\sigma_U = 186$ ksi
$\nu = 0.3$	
$E=30*10^6$ psi	

Number of cycle	$7*10^4$	10^5	$1.5*10^5$	$2*10^5$	$4*10^5$	$6*10^5$	10^6
$(\sigma_m)_{all}$	140	128	116	105	100	100	100
$(\sigma_e)_{all}$	116	100	86	83	83	83	83
$(\sigma_T)_{all}$	73.561	65 980	61 372	71 786	73 841	73 841	73 841
$K_M = (\sigma_m)_{all} / \sigma_U$	0 75	0 68	0 62	0 56	0 53	0 53	0 53
$K_T = (\sigma_T)_{all} / \sigma_U$	0 4	0 35	0 33	0 38	0 4	0 4	0 4

1020 Low carbon steel

ΔT 300 F	$(\sigma_T) = 40$ ksi
$\alpha = 9.61$ in/in F	$\sigma_U = 100$ ksi
$\nu = 0.3$	
$E=29*10^6$ psi	

Number of cycle	$4*10^5$	$6*10^5$	$8*10^5$	10^6	$1.5*10^6$	$2*10^6$	$4*10^6$	10^7
$(\sigma_m)_{all}$	78	74	70	68	63	63	63	63
$(\sigma_e)_{all}$	70	66	62	60	57	54	54	54
$(\sigma_T)_{all}$	96 47	88 5	82 2	85	94	77	77	77
$K_M = (\sigma_m)_{all} / \sigma_U$	0 78	0 74	0 7	0.68	0 63	0 63	0.63	0.63
$K_T = (\sigma_T)_{all} / \sigma_U$	0 91	0 88	0 82	0 85	0 94	0 77	0 77	0 77

Table 3-2 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=10 in., Mg=2)

mg=2 Cd=10

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.908045	0.847802	0.808255	0.779111	0.756431	0.738228	0.723169	0.710684	0.700175	0.691179
18	0.926182	0.900078	0.881408	0.866940	0.854188	0.843378	0.833767	0.825154	0.817277	0.810134
19	0.938114	0.919544	0.906457	0.895453	0.87544	0.865969	0.857303	0.849571	0.842481	0.835819
20	0.946991	0.927342	0.913092	0.901563	0.891767	0.883178	0.875482	0.868522	0.862122	0.856107
21	0.953643	0.936494	0.923815	0.913516	0.904723	0.896888	0.890047	0.88373	0.877817	0.872253
22	0.958312	0.943853	0.932493	0.923224	0.915082	0.908276	0.901973	0.896223	0.890921	0.885962
23	0.962766	0.949813	0.939654	0.931263	0.924051	0.917574	0.911524	0.905968	0.900814	0.895999
24	0.967525	0.954971	0.945692	0.938022	0.931442	0.925511	0.920048	0.915023	0.911042	0.906386
25	0.970668	0.959254	0.950762	0.943776	0.937748	0.932358	0.927554	0.923114	0.919003	0.915163
26	0.973352	0.962521	0.955141	0.948723	0.943181	0.938251	0.933734	0.929587	0.925741	0.922327
27	0.975954	0.966092	0.958939	0.953023	0.947904	0.943247	0.938213	0.935414	0.931388	0.928598
28	0.977874	0.968558	0.962247	0.95673	0.95243	0.947814	0.943978	0.940448	0.93715	0.934
29	0.979434	0.97126	0.965158	0.960067	0.956633	0.951757	0.948187	0.9449	0.941844	0.93858
30	0.980858	0.973422	0.967735	0.963017	0.958917	0.955254	0.951029	0.948458	0.946011	0.943321

Table 3-3 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth (C_d=20 in., Mg=2)

$\frac{1}{\sqrt{1+K}}$

Mg=2 Cd=20

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.830111	0.78198	0.760764	0.737115	0.716127	0.701873	0.694128	0.678652	0.669085	0.654275
18	0.868046	0.82515	0.797611	0.775485	0.757901	0.74282	0.729033	0.718438	0.708121	0.699792
19	0.894157	0.849751	0.824893	0.804479	0.789232	0.776362	0.765233	0.755441	0.747112	0.739188
20	0.911983	0.868522	0.845494	0.827442	0.81248	0.799904	0.788254	0.778179	0.769033	0.760673
21	0.923616	0.88373	0.862751	0.846172	0.832345	0.8204	0.809885	0.800412	0.791826	0.783859
22	0.932224	0.896223	0.877835	0.861760	0.848992	0.837981	0.828076	0.819034	0.811183	0.803743
23	0.931262	0.90668	0.889084	0.874594	0.863136	0.85262	0.843653	0.835361	0.827626	0.820372
24	0.938022	0.915823	0.898316	0.885302	0.875292	0.865094	0.857122	0.849377	0.84229	0.835748
25	0.943776	0.923114	0.906148	0.894131	0.885439	0.876079	0.868096	0.86109	0.854653	0.848651
26	0.948727	0.929082	0.913824	0.901809	0.894063	0.885688	0.87719	0.872379	0.866124	0.860331
27	0.953023	0.934414	0.920545	0.912092	0.901164	0.893466	0.885315	0.881817	0.876932	0.871573
28	0.95678	0.940445	0.92647	0.918719	0.910378	0.90033	0.892427	0.889409	0.8848017	0.879718
29	0.960087	0.9449	0.931703	0.924827	0.916784	0.907594	0.900674	0.893067	0.89279	0.88792
30	0.963017	0.948681	0.936404	0.929855	0.922516	0.913925	0.9117771	0.9046354	0.898899	0.8963096

Table 3-4 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=50 in Mg=2)

$\frac{1}{\sqrt{1+K}}$ Mg=2 Cd=50

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=50	HP=70	HP=80	HP=90	HP=100
17	0.696929	0.634204	0.595525	0.567863	0.548424	0.529002	0.514371	0.501779	0.490779	0.480930
18	0.739512	0.678580	0.640827	0.613471	0.592980	0.574527	0.558702	0.545887	0.535618	0.525678
19	0.771188	0.713611	0.67724	0.650547	0.629472	0.612043	0.597302	0.584484	0.573131	0.562997
20	0.796035	0.742434	0.707636	0.681765	0.6612	0.644128	0.629536	0.616815	0.605541	0.595420
21	0.817852	0.766714	0.723406	0.70881	0.688884	0.67201	0.657715	0.645158	0.63407	0.624068
22	0.836338	0.787502	0.755894	0.722018	0.712755	0.696587	0.682852	0.670408	0.659463	0.649884
23	0.850492	0.805412	0.775493	0.752635	0.734087	0.718447	0.704913	0.69298	0.682307	0.672053
24	0.863458	0.821282	0.792772	0.770925	0.75311	0.73808	0.724915	0.713324	0.702928	0.693505
25	0.874794	0.835135	0.808112	0.787251	0.770188	0.755636	0.742876	0.731745	0.721546	0.712473
26	0.88474	0.847434	0.821808	0.801815	0.785538	0.771585	0.759352	0.748401	0.738702	0.72978
27	0.89352	0.858395	0.834084	0.815118	0.799420	0.786018	0.774251	0.763782	0.754289	0.745648
28	0.901210	0.86821	0.845141	0.82706	0.812055	0.79817	0.787847	0.777720	0.768573	0.760204
29	0.908273	0.877035	0.855138	0.837608	0.823541	0.811179	0.800884	0.790636	0.781694	0.773508
30	0.91451	0.885002	0.864201	0.84778	0.834027	0.822140	0.811089	0.802305	0.793773	0.785949

Table 3-5 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=10 in Mg=5)

$\frac{1}{\sqrt{1+K}}$ Mg=5 Cd=10

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.933567	0.909567	0.89253	0.878912	0.867236	0.857154	0.848167	0.840030	0.83269	0.825869
18	0.950876	0.940579	0.928823	0.91883	0.910564	0.903228	0.896637	0.890628	0.885096	0.879956
19	0.967279	0.954636	0.945264	0.937573	0.930851	0.925084	0.919765	0.914834	0.910448	0.906263
20	0.973555	0.963190	0.955473	0.949102	0.943594	0.938606	0.934253	0.930183	0.926405	0.922873
21	0.977860	0.969165	0.962947	0.957121	0.952415	0.94822	0.944411	0.940887	0.937951	0.934002
22	0.981022	0.973471	0.967784	0.963084	0.958991	0.955336	0.952011	0.948947	0.946096	0.943423
22	0.983461	0.976884	0.97168	0.967716	0.964108	0.960881	0.957942	0.95523	0.952794	0.950332
24	0.985402	0.979530	0.975111	0.971424	0.968211	0.965333	0.962705	0.960205	0.958026	0.955903
25	0.986983	0.981738	0.97777	0.974462	0.971575	0.968987	0.966625	0.964442	0.962405	0.960491
26	0.988296	0.983567	0.979984	0.976994	0.974382	0.972039	0.969899	0.967919	0.966071	0.964383
27	0.989403	0.985111	0.981856	0.979135	0.976758	0.974622	0.972673	0.970868	0.969181	0.967594
28	0.990347	0.986420	0.983455	0.980966	0.978782	0.976830	0.975081	0.973397	0.97185	0.970356
29	0.991161	0.987507	0.984836	0.982551	0.980592	0.978754	0.97711	0.975587	0.974162	0.972822
30	0.991868	0.988589	0.98604	0.983932	0.982063	0.980426	0.978907	0.977409	0.976183	0.974942

Table 3-6 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=20 in , Mg=5)

					$\frac{1}{\sqrt{1+K}}$			Mg=5	Cd=20
Np	**HP=10**	**HP=20**	**HP=30**	**HP=40**	**HP=50**	**HP=60**	**HP=70**	**HP=80**	**HP=90**	**HP=100**
17	0.870412	0.840086	0.813017	0.793143	0.775331	0.762017	0.749529	0.738441	0.728463	0.718389
18	0.91849	0.890629	0.870829	0.854775	0.841503	0.830021	0.819867	0.810743	0.802445	0.794027
19	0.937573	0.914034	0.898632	0.885548	0.874478	0.864821	0.856217	0.848428	0.841317	0.834746
20	0.949102	0.930183	0.916409	0.905201	0.895765	0.887744	0.879961	0.873206	0.866963	0.861318
21	0.957131	0.940907	0.929409	0.918323	0.911035	0.903732	0.897188	0.891187	0.885876	0.880587
22	0.963584	0.948847	0.938511	0.928976	0.922547	0.915167	0.910327	0.904991	0.900064	0.895477
23	0.967716	0.95523	0.94597	0.93837	0.931823	0.926021	0.92078	0.91598	0.911541	0.9074
24	0.971424	0.960285	0.951953	0.945166	0.939272	0.934038	0.9293	0.924585	0.920829	0.9171[illegible]
25	0.974462	0.964442	0.956[illegible]	0.950785	0.945444	0.940891	0.936393	0.932428	0.928755	0.925382
26	0.976994	0.967318	0.961135	0.955586	0.950437	0.946299	0.942381	0.938874	0.935377	0.93322[illegible]
27	0.979135	0.970994	0.964864	0.959525	0.955005	0.951086	0.94747	0.944141	0.941047	0.938148
28	0.980968	0.973397	0.967704	0.963063	0.958879	0.955214	0.951891	0.948808	0.945951	0.943273
29	0.982551	0.975587	0.970342	0.965985	0.962195	0.958857	0.955723	0.952878	0.95003	0.947745
30	0.983932	0.977409	0.972646	0.968614	0.965181	0.961986	0.959094	0.956452	0.95399	0.951679

Table 3-7 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=50 in Mg=5)

					$\frac{1}{\sqrt{1+K}}$		Mg=5	Cd=50	
Np	**HP=10**	**HP=20**	**HP=30**	**HP=40**	**HP=50**	**HP=60**	**HP=70**	**HP=80**	**HP=90**	**HP=100**
17	0.758743	0.69074	0.662702	0.63570[illegible]	0.614510	0.597041	0.58222	0.569373	0.558048	0.547937
18	0.827371	0.770096	0.745734	0.731377	0.711768	0.685383	0.671272	0.658881	0.647066	0.637938
19	0.863583	0.820188	0.791603	0.769847	0.751815	0.736685	0.723549	0.711933	0.701517	0.692075
20	0.885502	0.848362	0.822884	0.803851	0.788732	0.772804	0.760629	0.749798	0.740035	0.731144
21	0.902029	0.869111	0.84518	0.830182	0.813222	0.800389	0.789108	0.779028	0.769901	0.761558
22	0.914653	0.885186	0.864411	0.847049	0.834371	0.822425	0.811064	0.80258	0.794056	0.786234
23	0.924663	0.895087	0.879175	0.864134	0.8515	0.840543	0.830831	0.822088	0.814133	0.806797
24	0.932813	0.908652	0.891402	0.877558	0.8658	0.855742	0.846709	0.838554	0.831105	0.824239
25	0.939677	0.917509	0.901603	0.88853	0.878134	0.868088	0.86027	0.853653	0.845871	0.839538
26	0.945281	0.925187	0.910473	0.895881	0.888627	0.879838	0.871964	0.864964	0.858322	0.852275
27	0.950151	0.93158	0.918048	0.907083	0.897744	0.889544	0.882186	0.875531	0.869387	0.863708
28	0.954353	0.937184	0.924638	0.914436	0.905722	0.898354	0.891173	0.884987	0.879143	0.873791
29	0.958011	0.943103	0.93042	0.920902	0.912754	0.90557	0.898113	0.893223	0.887788	0.882753
30	0.961318	0.948436	0.935527	0.926625	0.918[illegible]	0.912247	0.906178	0.900632	0.895617	0.890758

Table 3.8 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=10 in., Mg=10)

						$\frac{1}{\sqrt{1+K}}$		Mg=10	Cd=10	
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.887708	0.841887	0.8009411	0.7609065	0.7261712	0.6964845	0.6706491	0.6482531	0.6287079	0.6093007
18	0.877096	0.838725	0.8011181	0.7655548	0.7309883	0.7013048	0.6742414	0.6507956	0.6305439	0.332209
19	0.883418	0.8767763	0.8717184	0.8678288	0.8640011	0.8601779	0.8563826	0.8525111	0.8485679	0.8445306
20	0.8848937	0.8818744	0.8778382	0.8734372	0.8687478	0.8638079	0.8586599	0.8534318	0.8482278	0.8430348
21	0.885241	0.884885	0.8815851	0.8776622	0.8734411	0.8742445	0.8722687	0.8704381	0.864726	0.8671116
22	0.9006489	0.8971887	0.8943775	0.8920038	0.8899004	0.8878114	0.8856422	0.8743858	0.87239	0.8702911
23	0.902134	0.898493	0.8948493	0.8944491	0.8928004	0.8910059	0.879584	0.878812	0.8765444	0.8757427
24	0.9031111	0.8992299	0.8964187	0.8963622	0.8947889	0.893373	0.8920977	0.8908175	0.87378	0.8726459
25	0.9036858	0.9014133	0.8995511	0.8979999	0.8965077	0.8950246	0.8934104	0.8922032	0.8910275	0.8898164
26	0.904545	0.9023152	0.9004609	0.8990179	0.8975278	0.8960705	0.8945994	0.8934064	0.8922022	0.8910275
27	0.9055857	0.9033073	0.9015136	0.8992248	0.8981113	0.8969082	0.8957156	0.8945288	0.8933474	0.8921287
28	0.9065645	0.9037188	0.9023323	0.9011151	0.8994122	0.8981844	0.8968364	0.8955753	0.8943113	0.8931115
29	0.9069839	0.9043722	0.9029268	0.9016126	0.9002888	0.89914	0.8979054	0.8966813	0.8954299	0.8941956
30	0.9042281	0.9047511	0.9033853	0.9020691	0.8991739	0.8980881	0.8969467	0.8958544	0.8946963	0.8934976

Table 3.9 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=10 in., Mg=10)

						$\frac{1}{\sqrt{1+K}}$		Mg=10	Cd=20	
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.9203665	0.8928331	0.8729906	0.8571555	0.8443402	0.8320681	0.8226447	0.8136177	0.8054082	0.7978566
18	0.9055648	0.8836796	0.8705222	0.8616441	0.850511	0.8409488	0.8337553	0.8270629	0.8211982	0.8767
19	0.9071526	0.8951111	0.8853829	0.88421	0.8815648	0.8758533	0.87259	0.91577	0.8711321	0.8671722
20	0.9179372	0.9143318	0.9088116	0.9045261	0.9004894	0.8965173	0.8932094	0.8902522	0.8875228	0.8850006
21	0.9188222	0.9154335	0.9104144	0.9059935	0.9034414	0.9003182	0.8957118	0.8943347	0.8920122	0.893278
22	0.9220223	0.9188659	0.9039481	0.9064931	0.9031886	0.8976905	0.8954437	0.8951518	0.8939787	0.8962747
23	0.9244451	0.921022	0.9175319	0.9096006	0.9041189	0.9031419	0.9003869	0.8977844	0.8955413	0.8953198
24	0.9263362	0.9230479	0.9167735	0.9123867	0.9079052	0.903787	0.8999844	0.8962806	0.8960841	0.8959959
25	0.9279096	0.9253244	0.9173326	0.9172811	0.9135457	0.9071153	0.9039241	0.9059998	0.8949797	0.8931163
26	0.9264170	0.9247095	0.9214777	0.9178702	0.9178277	0.9151	0.9121111	0.91021	0.9083511	0.9067353
27	0.9292645	0.9262758	0.9232263	0.9207721	0.9178574	0.9178	0.9147758	0.9121753	0.9121563	0.9120963
28	0.9301181	0.9275652	0.924842	0.9225321	0.920053	0.9178731	0.9178841	0.91555	0.9141135	0.9127952
29	0.9311928	0.9285641	0.9261413	0.9240401	0.9222119	0.9205567	0.9190068	0.917566	0.9163152	0.9151271
30	0.9286011	0.9255844	0.9272881	0.9253644	0.9238778	0.9225168	0.9212744	0.9201487	0.9191283	0.9171149

Table 3.10 Design factor $1/\sqrt{(1+K)}$ versus load and number of teeth for (C_d=50 in Mg=10)

$\frac{1}{\sqrt{1+K}}$ mg=10 Cd=50

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.830071	0.781275	0.749164	0.724985	0.705481	0.689154	0.675	0.662762	0.65517	0.64106
18	0.898748	0.864967	0.841442	0.823102	0.807866	0.794802	0.783329	0.773064	0.763819	0.755355
19	0.924472	0.897830	0.878895	0.863520	0.851167	0.840192	0.830465	0.821706	0.813731	0.806395
20	0.935376	0.917305	0.901389	0.88859	0.877757	0.868267	0.859852	0.852228	0.84624	0.83878
21	0.949435	0.930626	0.918924	0.905434	0.896319	0.885105	0.880[illegible]	0.873539	0.867744	0.86200
22	0.95[illegible]8	0.940459	0.928487	0.91673	0.910399	0.903044	0.896442	0.890429	0.884983	0.87973
23	0.96243	0.948064	0.937464	0.928802	0.921366	0.914792	0.90887	0.90346	0.89846	0.8938
24	0.96691	0.954139	0.944[illegible]	0.93690	0.930222	0.9243	0.918953	0.914059	0.909532	0.905317
25	0.97056	0.959106	0.950566	0.94357	0.93753	0.93216	0.92730	0.922857	0.91872	0.91487
26	0.97358	0.963247	0.955525	0.94916	0.943859	0.938766	0.934332	0.930262	0.926497	0.92296
27	0.976134	0.96673	0.95970	0.9539	0.948869	0.94436	0.940324	0.936584	0.93311	0.92987
28	0.97830	0.969725	0.96321	0.957965	0.953347	0.949221	0.94549	0.942044	0.93884	0.93584
29	0.980179	0.97230	0.96633	0.961484	0.957233	0.95334	0.949975	0.946752	0.94363	0.94106
30	0.98190	0.974551	0.96900	0.964566	0.960[illegible]2	0.957166	0.953807	0.950955	0.94820	0.94582

Table 3.11 Design factor $\frac{(\sigma_w \ \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth For (C_d=10 in Mg=2)

$\frac{\sigma_w \ \sigma_r}{\sqrt{1+K}}$ Mg=2 Cd=10

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.860252	0.831773	0.800871	0.770629	0.738571	0.703333	0.664045	0.620115	0.571088	0.518622
18	0.887771	0.857158	0.833252	0.811478	0.789046	0.767624	0.743882	0.718213	0.690347	0.660613
19	0.900531	0.877442	0.854471	0.836585	0.820377	0.803877	0.786948	0.769238	0.750481	0.730463
20	0.90904	0.887188	0.869828	0.855086	0.841383	0.828132	0.814904	0.801400	0.787426	0.772801
21	0.917207	0.897102	0.881858	0.868895	0.857122	0.845961	0.835021	0.824064	0.812858	0.80151
22	0.923144	0.905052	0.891405	0.875872	0.869507	0.859882	0.850442	0.841214	0.831904	0.822574
23	0.927924	0.911578	0.899238	0.888847	0.879572	0.870588	0.862758	0.854755	0.846825	0.838868
24	0.931903	0.917031	0.905787	0.896337	0.887941	0.880203	0.872877	0.865798	0.85885	0.85183
25	0.935253	0.921851	0.911342	0.902686	0.895019	0.887566	0.881367	0.875215	0.868824	0.862714
26	0.938134	0.925813	0.91811	0.904135	0.901085	0.89464	0.888502	0.882839	0.877254	0.871770
27	0.940612	0.929042	0.920244	0.91286	0.906341	0.900396	0.894846	0.888871	0.884483	0.879518
28	0.94277	0.932037	0.923858	0.916892	0.910935	0.905422	0.900288	0.895427	0.890755	0.886215
29	0.944863	0.93467	0.927048	0.920633	0.914983	0.909847	0.905076	0.900587	0.89625	0.892[illegible]
30	0.946335	0.937001	0.929803	0.923862	0.918572	0.913780	0.909314	0.905114	0.901102	0.897225

Table 3-12 Design factor $\frac{(\sigma_{xi}\ \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=20 in Mg=2)

	$\frac{\sigma_{xi}\ \sigma_r}{\sqrt{1+K}}$						Mg=2	Cd=20		
Np	HP=16	HP=20	HP=32	HP=40	HP=56	HP=80	HP=76	HP=80	HP=80	HP=160
17	0.885965	0.7558811	0.721511	0.934877	0.570002	0.84784	0.825533	0.8465553	0.5827888	0.5604222
18	0.852691	0.7283587	0.7596677	0.7358295	0.7184577	0.8027245	0.8688594	0.8646932	0.6491192	0.6324885
19	0.8528896	0.81436	0.7572521	0.7602204	0.748774	0.7321855	0.7175595	0.7538027	0.9098	0.6782931
20	0.888077	0.8335651	0.8842654	0.7839138	0.7735563	0.7551165	0.7481223	0.7341427	0.7226668	0.7117783
21	0.8455956	0.8483941	0.8207858	0.8091181	0.7841226	0.7809069	0.7668936	0.7528154	0.7479408	0.7382954
22	0.86586	0.8315811	0.8412775	0.8259014	0.8112216	0.7930056	0.7853179	0.7781153	0.7658423	0.7561417
23	0.8978467	0.87213	0.8534463	0.8384447	0.825868	0.8144653	0.8043448	0.7952782	0.7884472	0.7783378
24	0.9047446	0.8910553	0.8638427	0.8499037	0.8384811	0.8271843	0.8161242	0.8059031	0.8016137	0.7941134
25	0.910538	0.8887222	0.872794	0.85987	0.8448278	0.8309092	0.8205116	0.8222011	0.8148244	0.8078533
26	0.9155168	0.8953963	0.8805772	0.8685532	0.8552222	0.8451117	0.8340605	0.8333709	0.8260398	0.8190458
27	0.9194448	0.9011156	0.8873847	0.8761142	0.8666432	0.8572668	0.8507252	0.8431888	0.8359834	0.8304844
28	0.9234232	0.9065255	0.8933868	0.8828773	0.87381	0.8658803	0.8588877	0.851991	0.8457402	0.8390664
29	0.9275077	0.9107762	0.8987731	0.8887335	0.8803498	0.8726823	0.8670576	0.8597858	0.8538191	0.84644
30	0.929922	0.9147772	0.9034855	0.894254	0.8861183	0.8789077	0.8729564	0.8667115	0.8612171	0.8560833

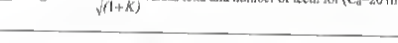
Table 3-13 Design factor $\frac{(\sigma_{xi}\ \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=50 in Mg=2)

	$\frac{\sigma_{xi}\ \sigma_r}{\sqrt{1+K}}$						Mg=2	Cd=50		
Np	HP=16	HP=20	HP=32	HP=40	HP=56	HP=80	HP=76	HP=80	HP=80	HP=160
17	0.9725211	0.868216	0.9693859	0.841243	0.516188	0.5008161	0.4851	0.4711336	0.4584678	0.4467761
18	0.7124477	0.6511888	0.6141132	0.886561	0.5843609	0.5403441	0.5315685	0.51987	0.5085568	0.4984849
19	0.7403525	0.6855323	0.6590132	0.623247	0.602997	0.5843703	0.5672071	0.5566304	0.5442277	0.5339137
20	0.7684788	0.7114529	0.973988	0.654009	0.633357	0.6161092	0.6013002	0.5893315	0.5767229	0.5662251
21	0.7890066	0.7364457	0.73532	0.680417	0.6603865	0.6438222	0.6291771	0.6164463	0.6051128	0.5941334
22	0.8063665	0.7585389	0.7272281	0.703428	0.6841011	0.6687835	0.653774	0.6413766	0.6302777	0.6209231
23	0.821162	0.7765152	0.7465357	0.7236692	0.7050278	0.6883494	0.675705	0.6637644	0.6528823	0.6436003
24	0.8339	0.791954	0.763517	0.7418511	0.7237779	0.7068	0.695304	0.6838837	0.673162	0.6638968
25	0.84501	0.8055557	0.778577	0.75769	0.74 536	0.7239922	0.7131103	0.7031824	0.6918877	0.6823851
26	0.8547453	0.8178615	0.7926877	0.772096	0.7556036	0.7415767	0.72827	0.7183033	0.7084482	0.6993677
27	0.8633441	0.8283012	0.8049858	0.7858469	0.7679295	0.7557813	0.7435973	0.733333	0.7237446	0.7143887
28	0.8709773	0.8371895	0.8149111	0.7962774	0.7787921	0.7681818	0.7572944	0.7477072	0.7378044	0.7293233
29	0.8777784	0.8455242	0.8247422	0.8074418	0.7902779	0.7805222	0.769353	0.7599772	0.7507741	0.7425112
30	0.8838891	0.8544494	0.8336222	0.8174748	0.8012888	0.7913088	0.7807754	0.7712353	0.762611	0.7546874

Table 3-14 Design factor $\frac{(\sigma_w \ \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=10 in , M_g=5)

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.876714	0.590083	0.533713	0.515514	0.5073[illegible]	0	0	0	0	0
18	0.910737	0.672977	0.641322	0.792215	0.752365	0.850726	0.884194	0.941152	0.969169	0.157397
19	0.924597	0.703537	0.682818	0.857406	0.823117	0.753745	0.7504.36	0.78074	0.943285	0.977206
20	0.932987	0.912343	0.901674	0.885684	0.867829	0.947198	0.933351	0.78677	0.764307	0.722857
21	0.938188	0.924597	0.912826	0.901282	0.888411	0.874955	0.859362	0.841751	0.831908	0.799716
22	0.942218	0.930563	0.920783	0.911503	0.901958	0.891739	0.881527	0.858147	0.854222	0.83122
23	0.945222	0.934969	0.925993	0.917035	0.908127	0.898433	0.888432	0.878113	0.874946	0.863856
24	0.947785	0.938552	0.931137	0.924414	0.917681	0.911243	0.904308	0.897034	0.893013	0.880456
25	0.949816	0.941448	0.93479	0.928044	0.921172	0.917522	0.911737	0.905697	0.69935	0.902469
26	0.951493	0.943856	0.937806	0.931463	0.927437	0.922508	0.917533	0.912408	0.907047	0.901295
27	0.952822	0.945892	0.940345	0.935454	0.930963	0.926513	0.922221	0.917782	0.913198	0.908414
28	0.954142	0.947537	0.942514	0.938045	0.933632	0.929587	0.926064	0.922185	0.918186	0.914033
29	0.955151	0.949148	0.944586	0.940204	0.936476	0.932778	0.93087	0.928669	0.926322	0.919681
30	0.956119	0.95047	0.946335	0.943181	0.939678	0.93537	0.932165	0.928935	0.926413	0.923579

Table 3-15 Design factor $\frac{(\sigma_w \ \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=20 in , M_g=5)



Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.834645	0.779627	0.753021	0.668903	0.577209	0.48144	0.368225	0.235505	0.0[illegible]5492	0
18	0.879078	0.844416	0.817556	0.787818	0.757748	0.724871	0.69188	0.647122	0.58136	0.509271
19	0.898304	0.873487	0.851578	0.832852	0.814221	0.795284	0.775313	0.753031	0.729824	0.7155[illegible]
20	0.911896	0.895533	0.879536	0.8577[illegible]	0.84332	0.830378	0.816864	0.802599	0.787711	0.772162
21	0.92049	0.901373	0.886882	0.874509	0.863227	0.852484	0.841403	0.831337	0.820525	0.809284
22	0.926948	0.910299	0.897537	0.888617	0.877182	0.868186	0.859484	0.850806	0.842381	0.83371
23	0.931998	0.917955	0.90639	0.898353	0.887801	0.880093	0.872649	0.865434	0.858317	0.851236
24	0.935896	0.922635	0.912519	0.904004	0.89545	0.889532	0.883903	0.878234	0.872614	0.866996
25	0.938982	0.927194	0.918[illegible]	0.910299	0.902483	0.897352	0.89142	0.885872	0.880473	0.875197
26	0.942033	0.931012	0.92283	0.915578	0.909158	0.903696	0.898418	0.893412	0.888586	0.883907
27	0.944362	0.934254	0.926541	0.920012	0.914332	0.908963	0.903432	0.898787	0.895435	0.8912[illegible]
28	0.946358	0.93704	0.929814	0.923925	0.91885	0.913582	0.908425	0.903245	0.901357	0.89741
29	0.948057	0.939437	0.932845	0.927283	0.922308	0.917944	0.913835	0.909574	0.906398	0.903767
30	0.949594	0.941572	0.935413	0.930297	0.92567	0.921623	0.917894	0.914111	0.910704	0.907438

Table 3-16 Design factor $\frac{(\sigma_w,\ \sigma\ )}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=50 in., Mg=5)

$\frac{\sigma_w \quad \sigma}{\sqrt{1+K}}$ Mg=5 Cd=50

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.725848	0.653576	0.621274	0.586316	0.554181	0.522603	0.490383	0.45671	0.421048	0.388016
18	0.774847	0.743755	0.709514	0.682745	0.660061	0.630765	0.602088	0.582517	0.555125	0.537516
19	0.808946	0.780307	0.756494	0.733235	0.713408	0.696836	0.681522	0.667368	0.653895	0.641162
20	0.852900	0.814601	0.788185	0.767397	0.750019	0.734920	0.721443	0.70913	0.697691	0.686913
21	0.869458	0.835636	0.811709	0.792603	0.777112	0.763488	0.751184	0.740002	0.729944	0.720256
22	0.882094	0.85169	0.830107	0.812842	0.798506	0.785930	0.774733	0.764881	0.755188	0.746473
23	0.89811	0.864649	0.84488	0.829246	0.815961	0.804367	0.794017	0.784818	0.77587	0.767525
24	0.900203	0.875301	0.857280	0.842801	0.830526	0.819758	0.81019	0.80145	0.793416	0.785946
25	0.907032	0.884218	0.867847	0.854282	0.84288	0.832697	0.823063	0.815514	0.808318	0.800947
26	0.91274	0.891791	0.876488	0.864070	0.853484	0.844188	0.836835	0.828225	0.821208	0.814882
27	0.917615	0.898297	0.884116	0.872576	0.862765	0.854009	0.84618	0.838056	0.832473	0.826344
28	0.921881	0.903941	0.890759	0.879998	0.870768	0.862623	0.855286	0.848585	0.842384	0.836828
29	0.925484	0.908878	0.896858	0.886526	0.877878	0.870232	0.863335	0.857026	0.851193	0.845754
30	0.928696	0.913227	0.901739	0.892389	0.884168	0.876996	0.870490	0.864548	0.859082	0.853903

Table 3-17 Design factor $\frac{(\sigma_w,\ \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=10 in., Mg=10)

$\frac{\sigma_w \quad \sigma}{\sqrt{1+K}}$ 0 shows temperature rise is above yield temperature

Mg=10 Cd=10

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.794846	0.155247	0	0	0	0	0	0	0	0
18	0.915476	0.845913	0.720665	0.528231	0.263705	0	0	0	0	0
19	0.933993	0.906008	0.863654	0.801461	0.718877	0.606901	0.470394	0.305782	0.111591	0
20	0.941637	0.924660	0.902714	0.872775	0.83307	0.782358	0.718882	0.644263	0.555449	0.452062
21	0.945244	0.933737	0.918621	0.891754	0.876091	0.850488	0.815808	0.773766	0.724767	0.669180
22	0.948356	0.939272	0.926887	0.910703	0.881853	0.863841	0.851808	0.835675	0.805288	0.770316
23	0.951683	0.943096	0.934815	0.925528	0.915162	0.902476	0.887454	0.869834	0.849480	0.826062
24	0.953457	0.945946	0.939116	0.931603	0.923759	0.914334	0.903375	0.890684	0.876098	0.859462
25	0.9549	0.949177	0.942275	0.936285	0.925755	0.922355	0.913099	0.904408	0.893492	0.881142
26	0.95609	0.949984	0.944756	0.938819	0.934153	0.926368	0.92152	0.913587	0.905583	0.896876
27	0.957069	0.951485	0.946772	0.942258	0.9370	0.932597	0.927908	0.920992	0.91410	0.906817
28	0.957941	0.952755	0.948449	0.944406	0.940328	0.936032	0.931393	0.926313	0.920715	0.914637
29	0.958676	0.953840	0.949873	0.9462	0.942584	0.938802	0.934802	0.930482	0.925773	0.920602
30	0.959317	0.954764	0.951008	0.947725	0.944436	0.941087	0.937577	0.933834	0.929298	0.925421

Table 3-18 Design factor $\frac{(\sigma_u - \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=20 in-Mg=10)

$\frac{\sigma_u - \sigma_r}{\sqrt{1+K}}$ 0 shows temperature rise is above yield temperature Mg=10 Cd=20

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.827619	0.713752	0.22990	0	0	0	0	0	0	0
18	0.908353	0.868723	0.813894	0.748334	0.656548	0.543587	0.402887	0.234011	0	0
19	0.924442	0.902787	0.880379	0.853834	0.822352	0.781927	0.733936	0.677234	0.612132	0.537849
20	0.933439	0.917486	0.900277	0.881759	0.861442	0.840563	0.82548	0.797781	0.768397	0.736446
21	0.939317	0.928228	0.915067	0.901908	0.892234	0.870238	0.854673	0.848282	0.828662	0.809246
22	0.943347	0.9323	0.921437	0.914478	0.905875	0.896343	0.886217	0.875104	0.862852	0.84934
23	0.946851	0.936864	0.926988	0.921794	0.914728	0.907475	0.899824	0.89162	0.882746	0.873139
24	0.949078	0.940299	0.933483	0.927286	0.921348	0.915405	0.909282	0.902852	0.896019	0.888765
25	0.951079	0.943256	0.937077	0.931602	0.926457	0.921497	0.916503	0.911039	0.905522	0.899722
26	0.952721	0.945614	0.940011	0.935106	0.93055	0.926145	0.921763	0.917511	0.91272	0.907955
27	0.954164	0.947594	0.942472	0.938017	0.933919	0.930003	0.926155	0.922206	0.918365	0.914314
28	0.955202	0.949231	0.944564	0.940478	0.936748	0.933217	0.929781	0.926372	0.922835	0.919429
29	0.956787	0.950757	0.946369	0.942592	0.939185	0.935942	0.932834	0.929778	0.926722	0.923533
30	0.957178	0.952302	0.947911	0.944425	0.941253	0.938287	0.935445	0.93267	0.929918	0.927158

Table 3-19 Design factor $\frac{(\sigma_{ur} - \sigma_r)}{\sqrt{(1+K)}}$ versus load and number of teeth for (C_d=50 in-Mg=10)

$\frac{\sigma_u - \sigma_r}{\sqrt{1+K}}$ 0 shows temperature rise is above yield temperature Mg=10 Cd=50

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.785114	0.594175	0.59084	0.457527	0.288196	0	0	0	0	0
18	0.856821	0.819679	0.7776077	0.726278	0.7250312	0.6340437	0.5626898	0.4710818	0.36311	0.5112405
19	0.887226	0.85706	0.834351	0.8144564	0.7960306	0.7780084	0.7584078	0.734802	0.7109411	0.685422
20	0.903122	0.878285	0.853822	0.8442977	0.83633	0.817189	0.8044242	0.7917332	0.7778995	0.7657753
21	0.913805	0.892823	0.8768432	0.863781	0.8521895	0.841544	0.8314548	0.8216855	0.8120655	0.8024848
22	0.921585	0.903743	0.8884811	0.8778564	0.8679981	0.8583889	0.8508956	0.8422287	0.8344443	0.826748
23	0.927569	0.911271	0.898581	0.8884627	0.8801251	0.8721913	0.8647233	0.8577732	0.851334	0.8448538
24	0.93231	0.917753	0.906322	0.897747	0.8898222	0.8826781	0.8760991	0.8698191	0.8640079	0.8583451
25	0.936158	0.923052	0.9131588	0.9049651	0.897777	0.89132	0.8853841	0.8797832	0.874573	0.8695351
26	0.939365	0.927466	0.9183477	0.9109774	0.9044229	0.8985543	0.8931398	0.8868797	0.8803338	0.8767158
27	0.942064	0.931187	0.9228567	0.9159388	0.9100777	0.9048755	0.8999716	0.8951134	0.8897859	0.8868818
28	0.944364	0.93459	0.9268077	0.92047	0.9149268	0.9103045	0.9053274	0.9011222	0.8971211	0.8933992
29	0.946347	0.937451	0.9303411	0.924278	0.9191441	0.9149521	0.9102655	0.9063348	0.9026144	0.8991132
30	0.948071	0.939578	0.9330154	0.9278025	0.92227	0.9189328	0.9148598	0.9110602	0.9077478	0.9042177

CHAPTER 4
INVESTIGATION OF THE EFFECT OF SURFACE ROUGHNESS AND LUBRICATION ON MAXIMUM TEMPERATURE IN THE CONTACT ZONE

Lubricating Film

When two clean surfaces slide with no lubricant between them (dry condition) the friction force at the interface decreases slightly with sliding speed and is independent of contact area [27]. The friction resistance increases with the applied normal load on the surfaces and is dependent on the physical nature of the surface.

Sliding surfaces can be separated by a lubricant film so that there will be no direct contact between surfaces. Under such conditions the physical characteristics of the surfaces are insignificant for the friction. In this case, the friction of resistance is independent of load, and is generally proportional to the speed and the viscosity of the lubricant, and inversely proportional to the thickness of the lubricant film. When the lubricant film thickness is of the same dimension as the surface roughness the laws of hydrodynamics no longer apply. This case is called boundary friction, which can be the result of heavy load, starting from rest, slow sliding speed, and reversal of sliding direction.

For highly loaded lubricated cylindrical contacts, the film thickness is affected by the elastic deformation of the material. This regime is known as elastohydrodynamic lubrication. Under such conditions, with the assumption of smooth surfaces without asperities, a simplified film thickness equation is given by Dowson and Higginson, [35], as:

$$h = 5\times10^{-9}\sqrt{\mu_0 V_r R_x} \qquad (4.1)$$

where $V_r = \frac{V_1 + V_2}{2}$, is rolling velocity (4.2)

$$V = \omega_1 R_1$$

$V_2 = \omega_2 R_2$ is the surface velocities, [in/sec] or [cm/sec] (4.3)

$R_x = \frac{R_1 R_2}{R_1 + R}$ is effective radius [in] or [cm] (4.4)

and μ_0 is the lubricant viscosity at the inlet temperature, poise – gr / (cm) (sec)

The minimum hydrodynamic lubrication film thickness for compressible, isothermal smooth unlayered and fully flooded cylinders by a Newtonian lubricant is given by Hamrok and Jacobson in a dimensionless form [36] as

$$\frac{h}{R_x} = 3.07\left[\frac{\mu_0 V_r}{E_e R_x}\right]^{.71}\left[\alpha_r E_e\right]^{.57}\left[\frac{W_0}{E_e R_x}\right]^{-.11} \qquad (4.5)$$

where

$\frac{h}{R_x}$ dimensionless film thickness parameter

$\frac{\mu_0 V_r}{E_e R_x}$ dimensionless speed parameter

$\alpha_r E_e$ dimensionless materials parameter

$\frac{W_0}{E_e R_x}$ dimensionless load parameter and α_r is the pressure viscosity coefficient of the lubricant and μ_0 is the lubricant inlet temperature The effect of pressure on viscosity can be expressed as $\mu = \mu_0 e^{\alpha_r P}$ where μ is the viscosity at a given pressure P

The lubricant viscosity is highly influenced by the temperature Accordingly the thermal effect due to the generated heat on the lubricant should be considered when calculating the lubricant film thickness. A correction factor which is defined as a ratio of the thermal film thickness to that predicted by Isothermal theory [37] can be given as

$$CC_0 = \frac{1}{1+2.41\left[(1+14.8Z^{0.83})L^{0.64}\right]} \qquad (4.6)$$

where $Z = \frac{(V_1 - V_2)}{(V_1 + V_2)}$ is slide to roll ratio (4.6a)

$L = \frac{\mu_0 \beta V^2}{k_0}$ is thermal loading parameter (4.6b)

β the lubricant temperature-viscosity coefficient found in the viscosity model

k_0 the lubricant thermal coednctivity thee the dynamic viscosity including the thermal effect becomes,

$$\mu = \mu_0 e^{(\alpha_e P - \beta(T - T_{h-avg}))} \qquad (4.7)$$

The dimensionless film thickness which is a function of the slide to roll ratio (Z) and the thermal loading parameter (L), is therefore given as

$$\left(\frac{h}{R_x}\right)_{corr} = CC_0 \left(\frac{h}{R_x}\right)_{Isothermal} \qquad (4.8)$$

The thermal loading parameter can be negligible for low rolling speeds ($L<0.1$) However for high speeds or high viscosity lubricants it can lead to a substantial change in film thickness

Manufacturing Process and Surface Roughness

The surface of real bodies is not ideally smooth In machining engineering materials, surface roughness is created Surface roughness plays an important role in

machine design. During a metal cutting operation, a machined surface is created as a result of the movement the tool edge relative to the work piece. Although various factors affect the surface condition, it is generally accepted that the cutting parameters such as speed, feed rate, depth of cut and tool nose radius have significant influence on the surface geometry. The surface roughness improves with increasing machine tool stiffness, cutting speed, and tool nose radius, and decreasing feed rate [38-40].

Some other studies indicated that tool wear causes the surface finish to deteriorate rapidly and has a direct effect on the maximum roughness [41]. Based on an extensive experimental study using a lathe, Hasegawa et al. [42] developed a statistical relationship of peak to valley surface roughness, R_{max}, in terms of cutting speed, feed rate, depth of cut, and tool nose radius using a response surface method. The statistical relationship is given as

$$R_{max} = 625V^{-0.433} f^{0.813} d^{0.854} r^{-0.47} \qquad (4.9)$$

where V= cutting speed

f = feed rate

r = tool radius

d = depth of cut

A piecewise dynamic solution of the interaction between the tool and work piece system in turning is reported by Jang and Seireg [41]. A generalized computer based model is developed for predicting surface roughness for any given condition which takes into consideration all the important parameters influencing deterministic vibratory behavior of the machine tool-work piece system. The parameters considered in the simulations are the feed rate, cutting speed, depth of cut, radius of the cutting edge, the

dimensions of the work piece and the mass stiffness, and the damping of the machine structure as well as the cutting tool assembly They have utilized the simulation to develop generalized equation for surface roughness based on output from the vibratory model A generalized equation of the following form is developed

$$R_{max} = c\,V^{k1} f^{k2} d^{k3} r^{k4} \qquad (4\ 10)$$

The results as generated from the simulation for cutting conditions covering the practical range of applications are used in a regression analysis to obtain the best fit for the equation parameters C k_1 k_2 k_3 and k_4.

All the simulated results were curve-fitted to give the following equations

$C = 7\ 02\text{-}2\ 2(1\text{-}e^{-(\omega-29)/18.3})$

$k_1 = -0\ 3712+0\ 3712(1\text{-}e^{-(\omega-29)/21})$

$k_2 = 0\ 6302+1.3626(1\text{-}e^{-(\omega-29)/51.3})$

$k_3 = 0\ 5425\text{-}0\ 5425(1\text{-}e^{-(\omega-29)/10.3})$

$k_4 = -0\ 3419\text{-}0\ 6523(1\text{-}e^{-(\omega-29)/51.5})$

where ω = natural frequency of tool assembly (Hz)

These equations are applicable for the following conditions

$K_s > 10^8$ N/m

61 m/min $< V <$ 305 m/min

0 127 mm/rev $< f <$ 0 88 mm/rev

0 31 mm $< d <$ 0 71

0 79 mm $< r <$ 2 38

The Contact Between Rough Surfaces

When rough surfaces come into contact the contact is discrete (figure 4-1). The sum of these discrete contact areas forms the real contact area. The real contact area defines those parts of the surfaces where there is strong interaction between the bodies and determines the dimensions of the heat source in frictional heating. The surface damage to solids during sliding is also closely related to the size of the real contact area since the most stressed material near the surface are determined by the real contact dimensions. Formation of the real contact area under load occurs as a result of the interpenetration or compressive deformation of individual asperities.

Hertz's solution (1895) of the contact problem based on elasticity theory is widely used in calculating the real contact area for smooth solids. For the case of spherical surfaces, the contact area (A_r) changes with the load N according to the following relationship

$$A_r \propto N^{2/3} \qquad (4\ 11)$$

In 1939 Bowden and Tabor [43] established that the real area of contact is directly proportional to load. They consequently assumed that all real contacts are in the plastic state. Archard [44 45] calculated a whole range of "multistage" models for "spheres on spheres" and reached the conclusion based on elastic deformation that the real contact area follows the approximate relation

$$A_r \propto N^{34\ 43} \qquad (4\ 12)$$

In this model, newly formed contact points account for the increase of real contact area with an increase in load more than the increase in size of the existing contact points.

The Greenwood-Williamson surface model [46] treats the contact of two rough elastic surfaces as the contact of equivalent elastic rough surface and smooth elastic plane. This model is used to calculate the real area of contact for the rough surfaces. The rough surface is assumed to be covered with asperities whose summits are all spherical in shape and with constant asperity radius (R). The summit heights are randomly variable and uniformly distributed over a rough surface with a known density (D_{sum}) [summits per unit area]. The mean height of the summits lies above the mean height of the surfaces as a whole by the amount (u). The summit heights (z) are assumed to follow a normal or gaussian distribution with standard deviation (σ_s). The summit height distribution is assumed to be symmetrical about the mean summit height. This model contains three parameters as

a) R), the constant asperity radius

(σ_s) the standard deviation of the summit heights

c) (D_{sum}), the number of summits per unit area.

A method of determining the values of these parameters of the Greenwood-Williamson surface roughness model is discussed by McCool in reference [47] with the following simplifications

a) Summits on surfaces have the same height and curvature as peaks on profiles (e.g. measurements made along one arbitrary direction).

b) The number of summits per unit area is the square of the linear density of peaks along one direction.

c) The peak mean-plane established by the average height of profile peaks in a certain direction is the same as the summit mean surface

The root-mean-square height (R_q) and slope (Δ_q) of a profile, obtainable as output of a profile measuring instrument are used to determine the three parameters [R, σ_s, D_{sum}] needed for implementing the Greenwood Williamson model for an isotropic or equivalent isotropic surface. Figure 4-2 shows that a smooth surface whose height above the summit mean plane is (d) is situated at a distance [$h-d+u$] above the profile mean plane. The ratio (h/R_q) (h/σ_{rms}), often called the lubricant film parameter [also referred to as the specific film thickness (λ)] is found to be linearly related to (d/σ_s). For a specified (h/σ_{rms}) value given the roughness and profile data of the surface, the dimensionless separation (d/σ_s) and therefore the micro-contact conditions at that ratio can be determined by using a Greenwood-Williamson model.

Then, the area of contact ratio for different load and speed conditions is calculated using the following equation

$$\frac{A_c}{A_0} = \pi D_{sum} R \sigma \, F_1\left(\frac{d}{\sigma}\right) \qquad (4\text{-}13)$$

where, A_c and A_0 are the real contact area and the nominal contact area respectively, [in^2]

$$F_1\left(\frac{d}{\sigma}\right) = \int_{\frac{d}{\sigma_s}}^{\infty}\left(S-\frac{d}{\sigma_s}\right)\Phi(S)dS$$

Coefficient of Friction of Lubricated Sliding/Rolling Contact

There are many published empirical formulas for evaluating the coefficient of friction, which were developed by different investigators under different experimental conditions. Therefore they may not correlate with each other. All of these formulas are developed from test data in the thermal regime. Generalized empirical formulas are presented in three sliding/rolling conditions, which can then be used to construct the entire curve, as illustrated in figure 4-3. The first point is f_o, which gives the magnitude of

the rolling coefficient of friction. The second point is f_m, which gives the peak value of the coefficient of friction in the nonlinear region, which occurs at a sliding/rolling ratio between 0 to 0.27 ($0<s<0.27$). This point is also assumed to approximately define the end of the isothermal region. The third condition is the thermal coefficient of friction, f_t, after which the coefficient of friction is assumed to be almost independent of the slide/roll ratio. In this chapter our interest is going to focus on the thermal coefficient of friction because of the high sliding/rolling ratios, which are expected at the locations on the tooth surface where damage generally occurs.

In the thermal regime, where the sliding/rolling ratio > 0.27, the coefficient of friction can be presented as [27]

$$f = f_0 - f_0(1 - e^{b})] \tag{4.14}$$

where f_0 is the coefficient of friction at $h_0 = 0$ from figure 4-4

$$a = 0.0864 - 1.372\times10^{3}\left(\frac{S_{sc}}{R}\right)_c$$

$$b = -\frac{h_0}{\dfrac{R}{2.873\left(\dfrac{S_{sc}}{R}\right)_c - 2.143\times10^{-5}}} \tag{4.15}$$

where S_{sc} is the effective surface roughness from figure 4-5

$\left(\dfrac{S_{sc}}{R}\right)_c$ is the effective surface ratio, from figure 4-6

R is effective radius

h_0 is the oil film thickness as calculated by Dowson Higginson formula given in equation 4.1

The ratio h_0 / R in equation (4 15) represents the influence of the lubricant film. The ratio (S_{rms} / R), represents the influence of the surface condition resulting from a particular manufacturing process.

Temperature Rise Calculation in Lubricated Rough Surface Contact

In this study the temperature rise on the bulk surface and the asperities are calculated based on whether the rise resulted from frictional heat input or viscous heat generation.

The considered lubrication conditions are given as below

The bulk surface is always covered by the lubricant. Therefore, the temperature rise is calculated based on viscous heating

The asperity temperature rise is calculated based on frictional heating when the lubrication parameter $\lambda = \frac{h}{\sigma_{rms}} < 1\ 4$ implies some asperity interaction.

The asperity temperature rise is calculated based on viscous heating when lubrication parameter $\lambda = \frac{h}{\sigma_{rms}} > 1\ 4$ implies negligible asperity interaction

where, h is lubrication film thickness

σ_{rms} is asperities root mean square height

Temperature Rise Calculation Based on Frictional Heating

The temperature rise based on frictional heat input is given by equation (2 9) and rewritten below contains four different parametric groups:

Material parameters $\phi_1 (\nu, E, k, c)$

Geometric parameters $\phi_2 (M_e, N_e, \phi, x_e)$

Lubrication and surface parameters $\phi_3 (\psi, f, A_G, Ac)$

Application parameters $\phi_4(HP \quad \omega_p, C_d)$

$$\Delta T_p = \phi_1(\nu\rho, E, k, c) \times \phi_2(M_g, N_p \ \phi, x_d) \times \phi_3(\psi, f \ A_O/Ac) \times \phi_4(HP \quad \omega_p, C_d) \qquad (4\,16)$$

$$N_p = \frac{1}{\pi^{1/4}} \left(\frac{t}{\left(\frac{1-\nu_p^2}{E_p} + \frac{1-\nu_g^2}{E_g} \right)^{1/4} \sqrt{k/c}} \right) \left(\frac{\left(1+M_g\right)^{3/4} \left[1-\left(M_g+1\right)x_t \right] \sin^{1/4}\phi}{M_g^{3/4}(1-x_t)^{1/4} \cos^{3/4}\phi} \right) \left(\psi \frac{Ao}{Ac} \right) \left(\frac{Hp^{3/4}}{\omega_p^{1/4} C_d^{1/2}} \right) \quad (4\,17)$$

In this chapter the lubrication and the surface roughness parameters are the main focus considered These parameters are a function of coefficient of friction f, Ratio of nominal area of contact to real area of contact (Ao/Ac) and heat partition of coefficient ψ

The coefficient of friction is calculated by the procedure following the equation (4 14) and the ratio of nominal area to real area is calculated from Greenwood–Williamson model

Temperature Rise Calculation Based on Viscous Heating

Temperature rise due to viscous heating is analyzed using the procedure developed by Rashid and Seireg, which is given in reference (14) The model given in figure 4-7 is utilized to find the dimensionless temperature rise equations The model represents two rolling/sliding cylinders having different radii thermal properties and bulk temperatures, which are separated by a lubricant film with thickness h The heat generation zone with thickness w represents the liquid region where the lubricant undergoes a high shear rate At moderate to high sliding speeds the magnitude of w is assumed to be approximately 0 1h In order to simplify the derivation of the dimensionless equation for this case w is initially assumed to be equal to zero Then the equations are given as [26]

$$\frac{T_{01}-T_{s1}}{\psi q}=\frac{1.14}{k_0}\left(\frac{V_1\rho_1c_1h}{2k_0}\right)^{-0.[illegible]}\left(\frac{2b}{h}\right)^{0.05}\left(\frac{k}{k_0}\right)^{[illegible]}e^{\left(-0.00\times10^{[illegible]}\left(\frac{[illegible]}{2k_0}\right)\right)} \quad (4.18)$$

and

$$\frac{T_{s1}-T_{B1}}{\psi q}=\frac{1.03}{k_1}\left(\frac{\rho_1c_1V_1b}{k_1}\right)^{-0.5} \quad (4.19)$$

where T_{01} is the maximum fluid film temperature

T_{s1} is the maximum surface temperature

T_{B1} is the bulk temperature

ψ is the heat partition of coefficient (assumed 0.5)

V_1 is the roller speed

ρ_1 and ρ_0 are the densities of gear material and fluid

c_1 and c_0 are the specific heats of material and fluid

k_1 and k_0 are the conductive heat transfer coefficient of material and the fluid.

h is the film thickness.

b is the contact width.

The transient heat input q per unit contact length is calculated from shear stress S:

$$q=V_sbS \quad (4.20)$$

where V_s is the sliding velocity and S is the shear stress can be calculated approximately as

$$S=\mu\frac{V_s}{h} \quad (4.21)$$

Application to Gears

The applications to this study are undertaken using two extreme conditions for the viscosity. In the first, the viscosity is assumed to be constant at the inlet temperature and in the second, the viscosity is assumed to be constant at the maximum surface

temperature. Two different surface manufacturing processes, fine and the rough ground, are also considered. The properties of lubricant (oil 30) and the materials used are given in table 4-3

The calculations are done for load 10 Hp, gear ratios 2.5 and 10 the number of teeth Np between 17 to 36 and center distance C_d=10 in

Numerical Results

Case 1 Temperature rise is calculated for fine ground gears with the assumption of constant oil viscosity corresponding to an inlet temperature (80 ^{0}F) The results are given in tables 4-4 to 4-6.

Case 2 Temperature rise is calculated for rough ground gears with the assumption of constant oil viscosity corresponding to an inlet temperature (80 ^{0}F) The results are given in tables 4-7 to 4-9

Case 3 Temperature rise is calculated for fine ground gears with the assumption of constant oil viscosity corresponding to the maximum bulk surface temperature The results are given in tables 4-10 to 4-12

Case 4 Temperature rise is calculated for rough ground gears with the assumption of constant oil viscosity corresponding to the maximum bulk surface temperature. The results are given in tables 4-13 to 4-15

The viscosity temperature relationship used is given by the following equation

$$\mu(T) = \mu_o e^{b/(T-\theta)} \qquad (4.22)$$

where b is constant (for oil 30 b= 1361 ^{0}F)

T is the temperature (^{0}F)

θ is constant which is equal to 95 ^{0}F

μ_0 - is lubricant reference viscosity (μ_0=1.41x10^{-6} reyn)

In case 3 and case 4 the viscosity and the surface temperature found by iteration as illustrated in the flow chart in figure 4-8.

The results show that the temperature rise increases with the decrease of the number of teeth and the increase of the gear ratio. All the temperature calculations resulting from viscous shear input are based on the two extreme assumptions of oil film viscosity either at the inlet temperature or at the maximum surface temperature. Some of the temperature rise values calculated based on these assumptions are extremely high and should be considered only as representation of trends. More realistic calculations of shear heating have to take into consideration the change in the viscosity and other oil properties gradually with temperature and pressure within film contact zone. This consideration requires very intensive computations and is beyond the scope of this study.

From this investigation it can be assumed that the temperature rises on the surface and on the asperities are somewhere between the calculated temperatures based on the assumed extreme conditions.

The temperature rise based on viscous shear heat input is assumed to be independent of the load applied. Further calculations are done specifically for the temperature rise on the asperities for fine and rough ground gears subjected to loads between 10 to100 Hp and gear ratios of 2 and 10 respectively. The results of the calculations are given in table 4-8 to 4-11. The results show that the temperature rise is highly effected by the increase of gear ratio and decrease of number of teeth for the shear heat input case and also effected by load for the frictional heat input case. The surface roughness also affects the temperature rise indirectly. Fine ground gears are generally

subjected to viscous heat input, which reduces the temperature rise at the asperities Rough ground gears are generally subjected to frictional heat input due to the higher asperity height Accordingly the asperity temperature of the rough ground surface is generally higher than the fine ground surface although the bulk surface temperatures are same

Contact Stress Modification Factor in Lubricated Rolling/Sliding Contact

The same approach given in chapter 3 for contact stress modification is applied in this chapter using the temperature rises calculated in section 4 6 for the asperities in the lubricated condition The modification factors are calculated by using the equation (3 7) for high carbon steel (4340) and low carbon steel (1020) gears with rough and fine ground surfaces As in the case of the temperature rise calculations the viscosity of the oil film is based on both the inlet temperature maximum surface temperature assumptions

The results of the contact stress modification factors, K are given in tables 4-24 to39 The parameter $\frac{1}{\sqrt{1+K}} = \left(\frac{\sigma_m}{K_m \sigma_s}\right)$ which represents the mechanical component of the total allowable stress for a given number of cycles under the combined thermal and mechanical loading is also calculated and the results are given in tables 4-40 to 4-47 and plotted in figures 9 to 16 for viscosity based on inlet temperature and tables 4-48 to 4-55 figures 17 to 24 for viscosity based on maximum surface temperature

The results show that high carbon steel gears are significantly more affected by the thermal stress than low carbon steel gears Increasing the load also increases the effect of thermal stress Decreasing the number of teeth increases the effect of thermal stress. Fine ground gears are less influenced by thermal stress than rough ground gears

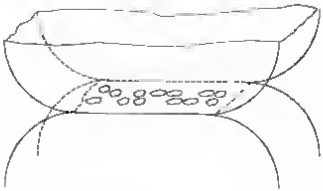


Figure 4-1 Rough surfaces in contact

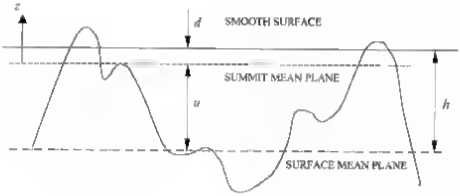


Figure 4-2 Contact of a rough surface and smooth plane

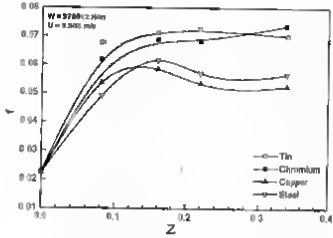


Figure 4-3 Variation of coefficient of friction with slide/roll ratio, Vs = 0.303 m/sec [27]

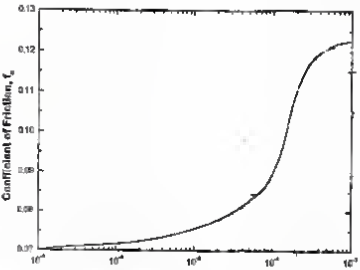


Figure 4-4 Coefficient of friction at $h_0/Req = 0$ against nominal S_{ss} / R [27]

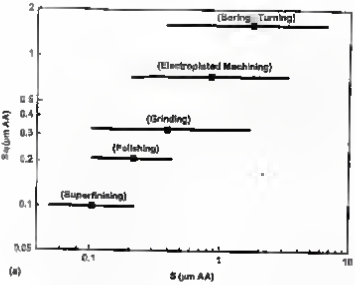


Figure 4-5 Proposed effective surface roughness for various manufacturing [27]

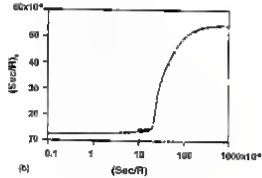


Figure 4-6 Effective $(S_{sc} / R)_e$ against nominal S_{sc} / R [27]

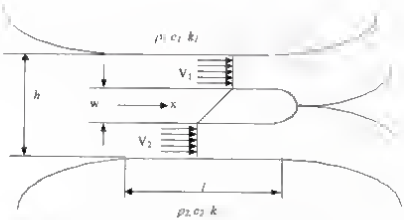


Figure 4.7 Lubricated, heavily loaded sliding/rolling cylinder [26]

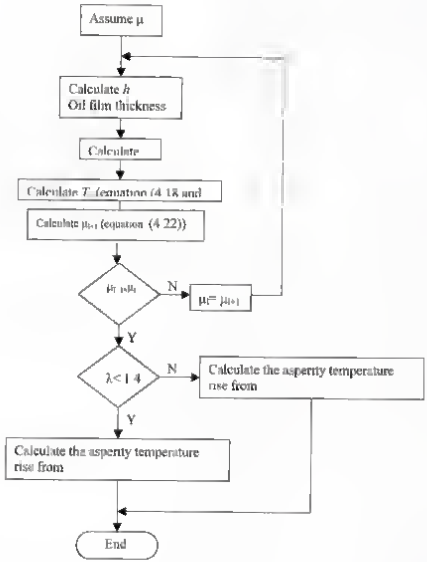


Figure 4-8 Flow chart of temperature rise calculation where viscosity constant at maximum surface

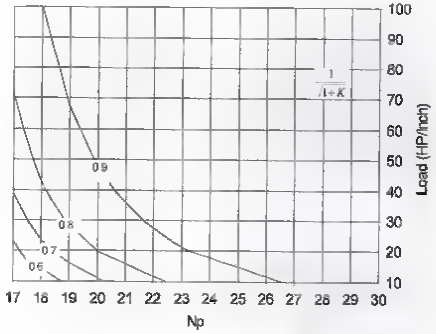


Figure 4-9 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 4340 high carbon steel gear, gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at inlet temperature

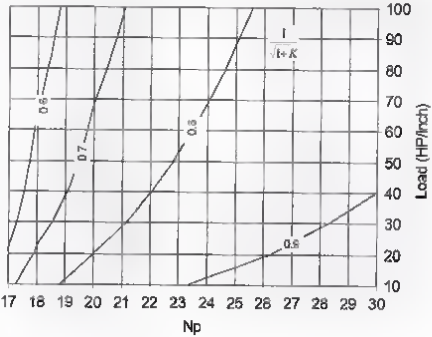


Figure 4-10 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 4340 high carbon steel gear, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at inlet temperature

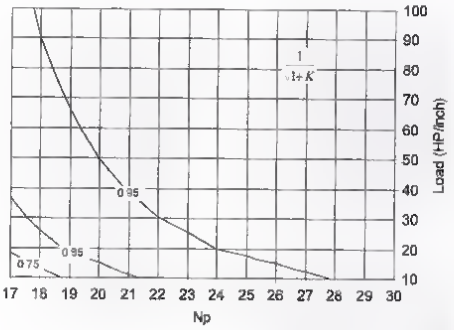


Figure 4-11 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 4340 high carbon steel gear. gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at inlet temperature

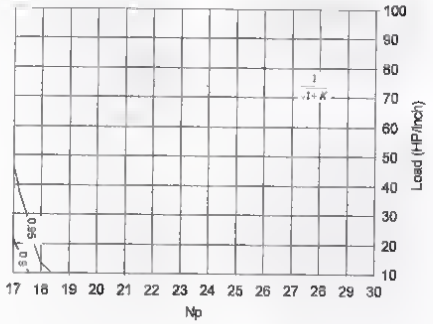


Figure 4-12 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 4340 high carbon steel gear gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

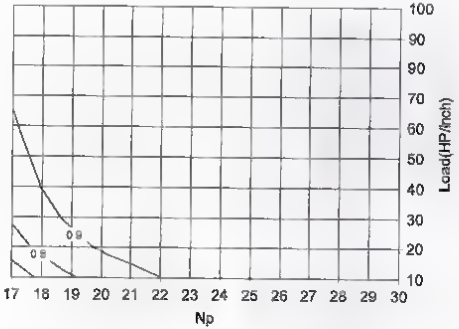


Figure 4-13 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 1020 low carbon steel gear-gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at inlet temperature

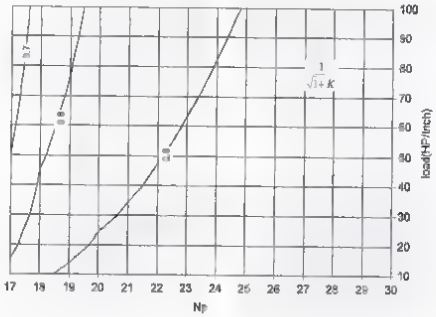


Figure 4-14 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 1020 low carbon steel gear, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at inlet temperature

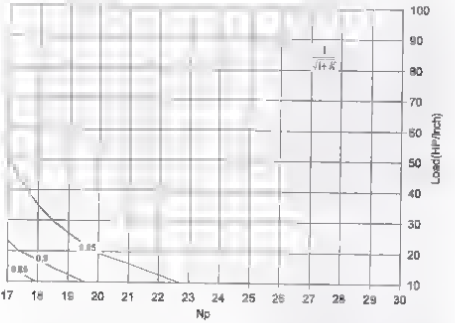


Figure 4-15 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 1020 low carbon steel gear, gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at inlet temperature

Figure 4-16 Design factor $1/\sqrt{(1+A)}$ versus number of teeth and load for fine ground and 1020 low carbon steel gear, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at inlet temperature

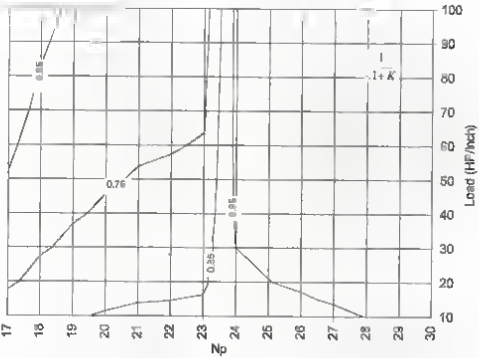


Figure 4-17 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 4340 high carbon steel gear gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at maximum surface temperature

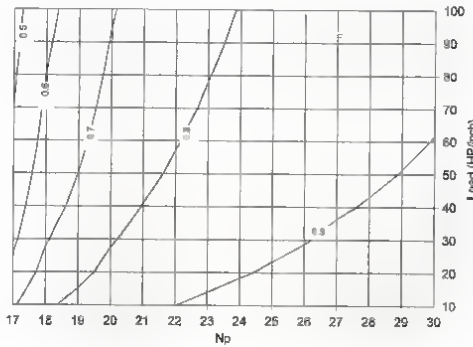


Figure 4-18 Design factor $1/\sqrt{(1+A')}$ versus number of teeth and load for rough ground and 4340 high carbon steel gear, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

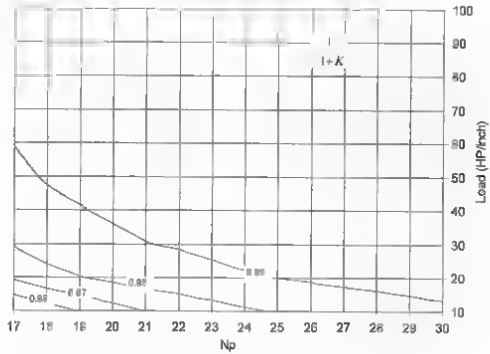


Figure 4-19 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 4340 high carbon steel gear gear ratio Mg=2 center distance Cd 10 and constant oil viscosity at maximum surface temperature

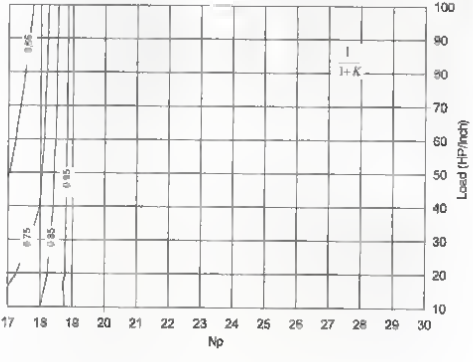


Figure 4-20 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 4340 high carbon steel gear gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at maximum surface temperature

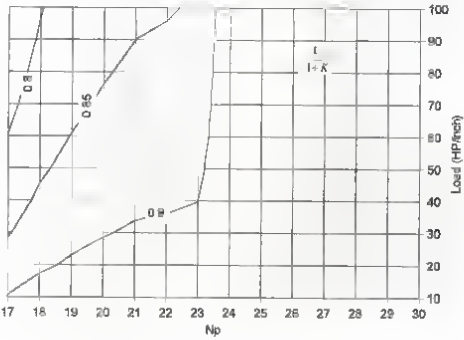


Figure 4-21 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 1020 low carbon steel gear gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at maximum surface temperature

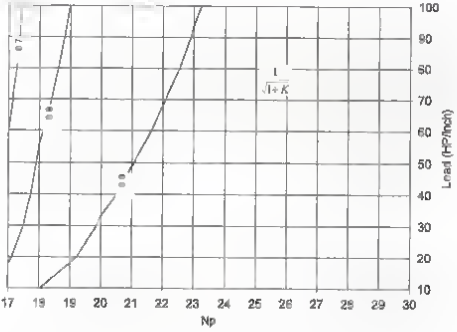


Figure 4-22 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 1020 low carbon steel gear gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at maximum surface temperature

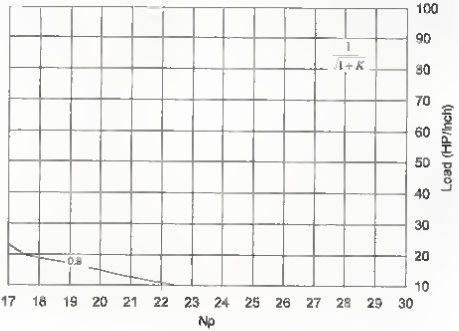


Figure 4.23 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 1020 low carbon steel gear gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at maximum surface temperature

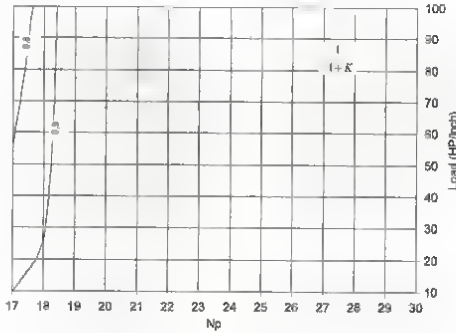


Figure 4-24 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 1020 low carbon steel gear gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

Table 4-1 Roughness and profile data for typical finishing operations

Surface Type	R_q μ in	Δq
Fine Ground	2 74	0 0147
Rough Ground	21 5	0 0901
Lapped	3 92	0 0525
Polished	1 70	0 0115
Shot Peened	45 9	0 079

Table 4 2 Greenwood-Williamson model input parameters calculated for surface roughness data given in (Table 4-1)

Surface type	α (bandwidth parameter)	R μm (asperity radius)	σ_s μm (std Deviation hts)	D_{max} (density-summ/mm^2
Fine Ground	517 89	6 54	0 097	7 30x 10^3
Rough Ground	32 01	5 48	0 75	2 77x 10^4
Lapped	15 49	4 25	0 14	1 36x 10^5
Polished	264 10	9 18	0 06	5 99x 10^5
Shot Peened	213 04	5 09	1 62	3 11x 10^4

Table 4-3 Lubricating oil and material thermal and mechanical properties

Gear specification

ω_p [rad /sec]	Φ [deg]
180	20

Material mechanical properties (steel)

Ep [psi]	Ec [psi]	b
$30*10^6$	$15*10^6$	0.3

Material thermal properties

K_l		C_l		ρ_l
[Btu/ in-F sec]	[lb-in/in-F sec]	[Btu/lb F]	[lb in/in F]	[lb/in^3]
$5.96*10^{-4}$	2.7	0.11	1148	$8.9*10^{-6}$

Lubricant thermal properties (SAE 30)

K_o [Btu/ in-F-sec]	C_o [Btu/lb-F]	ρ_o [lb/in^3]
$1.736*10^{-7}$	0.48	0.0315

Lubricant viscosity properties (SAE 30)

μ_o		l
[reyn]=[lbf sec/in^2]	Poise[0.1Pa sec]	
$1.41*10^{-5}$	$1.41*68947*10^{-6}$	1361

Table 4-4 Temperature rises on surface asperities and lubricant film temperatures versus number of teeth for fine ground, load 50 hp Gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at inlet temperature

Np	mu	lambda	h	Vs	Ts	Tssp	Tfs	Tfssp
17	5.715	17.819	48.825	595.647	381.800	404.155	7528.525	7566.819
18	3.715	50.180	56.283	249.857	266.000	298.188	6811.754	6847.890
19	3.715	55.080	60.527	238.510	224.000	234.941	5847.814	5882.388
20	3.715	25.655	68.868	227.648	195.545	161.518	5251.715	5539.457
21	3.715	25.416	68.827	217.956	155.889	169.251	4651.576	4684.505
22	3.715	28.226	71.860	208.144	131.558	158.717	4178.619	4211.541
23	5.715	27.250	74.883	200.195	113.089	119.415	3772.913	3803.572
24	3.715	28.177	77.204	192.466	100.019	103.815	3458.005	3449.166
25	3.715	28.866	79.447	185.493	89.852	91.555	3115.524	3140.267
26	3.715	29.732	81.454	180.065	79.233	82.098	2845.760	2869.455
27	3.715	30.309	83.289	175.555	71.325	73.848	2605.485	2631.037
28	3.715	31.003	84.949	168.518	64.660	66.841	2395.715	2420.113
29	3.715	31.537	86.465	163.630	58.936	60.832	2209.478	2233.771
30	3.715	35.085	87.859	159.063	55.825	55.833	2045.490	2065.755
31	5.715	32.535	89.140	153.484	48.481	51.100	1894.508	1918.518
32	5.715	32.965	90.324	149.009	45.629	47.119	1761.683	1781.941
33	3.715	33.362	91.422	144.852	42.238	45.102	1641.600	1660.845
34	3.715	33.738	95.443	140.941	38.521	40.477	1533.092	1551.575
35	3.715	34.096	93.395	137.228	35.928	37.667	1434.765	1452.414
36	3.715	34.416	94.284	133.709	34.111	35.153	1345.969	1362.290

Table 4-5 Temperature rises on surface, asperities and lubricant film temperatures versus number of teeth for fine ground load 50 hp Gear ratio Mg=5 center distance Cd=10 and constant oil viscosity at inlet temperature

Np	mu	lambda	h	Vs	Ts	Tssp	Tfs	Tfssp
17	3.715	9.635	15.548	114.854	484.744	485.558	1788.770	1874.255
18	5.715	7.340	20.111	108.627	248.805	578.758	1491.587	1558.389
19	3.715	8.772	23.707	103.302	182.641	181.156	1500.182	1322.165
20	5.715	9.764	26.754	98.444	151.302	144.128	1154.525	1181.545
21	3.715	10.661	29.265	94.025	103.555	113.978	1035.500	1047.188
55	3.715	11.475	31.454	90.067	85.081	29.538	955.918	945.576
23	5.715	12.187	33.337	86.585	71.875	78.139	850.859	858.854
24	3.715	12.784	35.758	82.872	61.448	66.700	777.298	784.500
55	3.715	13.337	36.944	79.755	53.491	57.258	715.389	719.168
26	5.715	13.837	37.914	76.855	48.851	50.810	656.857	645.114
27	3.715	14.565	38.160	74.092	41.651	44.792	609.687	611.665
28	3.715	14.707	40.568	71.585	37.223	39.885	565.223	566.709
29	5.715	15.089	41.344	69.510	33.510	36.013	525.404	551.750
30	3.715	15.441	42.030	66.825	30.348	35.475	488.855	468.769
31	5.715	15.787	43.202	64.958	27.856	30.025	454.887	458.584
55	5.715	16.078	44.151	63.279	26.273	28.974	455.832	458.776
33	3.715	16.355	44.803	61.746	25.515	24.745	389.268	402.408
34	5.715	16.616	45.525	60.418	21.408	22.705	375.563	378.511
35	3.715	16.861	46.208	67.785	19.805	21.271	553.341	356.553
36	5.715	17.093	46.854	56.536	18.383	18.540	533.581	336.628

Table 4-6 Temperature rises on surface asperrities and lubricant film temperatures versus number of teeth for fine ground, load 50 hp Gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at inlet temperature

Np	mu	lambda	h	Vs	Ts	Tasp	Tfs	Tfasp
17	3 716	2 358	5 633	55 416	474 505	824 662	636 153	1281 852
18	3 716	3 253	8 037	56 256	216 744	382 505	540 162	630 214
19	3 716	4 151	11 375	53 379	135 318	178 283	434 220	478 122
20	3 716	4 825	13 221	50 799	89 334	124 078	370 079	395 097
21	3 715	5 387	14 780	48 457	76 212	93 813	324 025	340 929
22	3 715	5 889	16 352	46 322	61 488	74 137	288 224	300 540
23	3 715	6 282	17 241	44 367	51 005	59 853	259 184	269 819
24	3 715	6 669	18 259	42 570	43 188	50 829	234 878	242 374
25	3 715	7 004	19 162	40 914	37 181	43 384	214 222	220 347
26	3 715	7 309	20 026	39 382	32 388	37 534	196 401	201 518
27	3 715	7 584	20 786	37 969	28 528	32 862	180 881	185 211
28	3 715	7 840	21 461	36 636	25 348	28 955	167 198	170 946
29	3 715	8 073	22 120	35 405	22 697	25 810	155 086	158 363
30	3 715	8 288	22 710	34 252	20 457	23 273	144 265	147 186
31	3 716	8 488	23 257	33 172	18 545	21 031	134 626	137 200
32	3 716	8 674	23 766	32 159	16 898	19 109	125 923	128 232
33	3 716	8 847	24 240	31 204	15 488	17 447	118 055	120 141
34	3 715	9 008	24 684	30 305	14 217	15 896	110 917	112 512
35	3 715	9 159	25 100	29 456	13 116	14 730	104 418	105 148
36	3 715	9 363	25 660	28 354	12 141	13 509	98 482	100 071

Table 4-7 Temperature rises on surface asperrities and lubricant film temperatures versus number of teeth for rough ground load 50 hp., Gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at inlet temperature

Np	mu	lambda	h	Vs	Ts	Tasp	Tfs	Tfasp
17	3 716	2 271	46 825	262 666	381 000	686 134	7626 325	7846 053
18	3 715	2 572	55 203	248 827	284 000	467 957	6611 724	6953 767
19	3 715	2 915	60 527	236 210	224 000	350 677	5847 614	6156 385
20	3 715	3 019	64 894	227 646	183 243	276 155	5201 783	5492 125
21	3 715	3 152	68 627	217 395	153 648	225 839	4651 576	4927 898
22	3 716	3 342	71 859	206 144	131 356	189 036	4178 819	4443 935
23	3 716	3 474	74 693	200 995	113 936	161 405	3772 813	4025 595
24	3 716	3 591	77 204	193 405	100 010	138 876	3420 002	3661 666
25	3 716	3 695	78 447	186 489	89 052	122 683	3112 324	3343 290
26	3 716	3 784	81 464	180 005	79 238	108 580	2842 760	3063 375
27	3 716	3 874	83 288	173 962	71 325	97 086	2605 485	2818 107
28	3 715	3 951	84 948	168 318	64 800	87 355	2395 712	2599 733
29	3 716	4 022	86 468	163 030	58 926	79 091	2209 478	2401 314
30	3 715	4 095	87 856	158 069	53 625	72 002	2043 480	2226 571
31	3 716	4 148	89 140	153 404	49 451	66 567	1894 995	2069 754
32	3 715	4 201	90 324	149 008	45 624	61 617	1761 643	1928 546
33	3 715	4 252	91 422	144 862	42 236	56 817	1641 800	1800 365
34	3 715	4 300	92 443	140 941	39 221	51 865	1533 092	1685 406
35	3 715	4 344	93 395	137 229	36 528	47 975	1434 750	1580 379
36	3 715	4 385	94 284	133 706	34 111	44 679	1345 388	1484 683

Table 4.8 Temperature rises on surface, asperities and lubricant film temperatures versus number of teeth for rough ground, load 50 hp., Gear ratio Mg=5, center distance Cd=10 and constant oil viscosity at inlet temperature

Np	mu	lambda	h	Va	Ta	Tasp	Tfa	Tfasp	Ac/Aa	f
17	3.715	0.709	15.249	114.824	494.744	736.000	1298.770		8.34E-02	0.117
18	3.715	0.935	20.111	108.687	240.000	473.000	1401.307		8.00E-02	0.108
19	2.715	1.100	22.777	103.302	198.641	383.000	1302.102		4.00E-02	0.138
20	3.715	1.244	26.754	98.444	139.302	300.000	1154.225		3.98E-02	0.099
21	3.715	1.361	29.265	94.025	103.252	256.000	1025.500		3.12E-02	0.090
22	3.715	1.462	21.434	89.987	85.081	270.230	835.010	1139.212		
23	3.715	1.561	33.337	86.282	71.675	202.703	950.000	999.169		
24	3.715	1.662	25.028	82.572	61.446	158.796	777.288	885.045		
25	3.715	1.200	36.544	79.722	53.401	130.200	713.090	800.010		
26	2.715	1.782	27.014	76.909	46.931	108.910	656.927	730.252		
27	2.715	1.921	38.159	74.052	41.631	92.758	606.067	676.103		
28	2.715	1.874	48.205	71.585	27.223	80.188	562.223	617.942		
30	3.715	1.982	41.344	69.208	33.510	70.187	522.498	572.003		
30	3.715	1.900	42.309	66.908	30.340	62.021	486.635	531.498		
31	3.715	2.009	43.202	64.928	27.630	55.290	454.697	495.297		
32	3.715	2.080	44.031	62.979	25.273	49.652	425.632	462.829		
33	3.715	2.084	44.803	61.148	23.215	44.874	399.258	433.557		
34	3.715	2.117	45.525	59.416	21.408	40.783	375.253	407.064		
35	3.715	2.148	46.200	57.780	19.809	37.240	353.341	383.002		
36	2.715	2.178	46.834	56.236	18.383	34.172	333.290	360.990		

Table 4-9 Temperature rises on surface asperities and lubricant film temperatures versus number of teeth for rough ground, load 50 hp., Gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

Np	mu	lambda	h	Va	Ta	Tasp	Tfa	Ac/Ac	f
17	3.715	0.282	5.933	59.418	474.505	1441.000	836.153	0.169	0.124
18	3.715	0.420	8.837	56.236	210.744	894.800	548.182	0.139	0.116
19	3.715	0.520	11.375	53.379	135.210	481.000	434.220	0.120	0.110
20	3.715	0.616	13.221	50.763	99.334	371.000	370.975	0.107	0.111
21	3.715	0.687	14.760	48.457	78.212	308.500	324.025	9.98E-02	0.110
22	3.715	0.740	16.082	46.322	61.496	264.000	284.220	8.92E-02	0.108
22	2.715	0.802	17.241	44.387	51.005	231.500	259.154	8.14E-02	0.105
24	3.715	0.858	18.289	42.570	43.190	206.400	234.878	7.50E-02	0.104
25	3.715	0.892	19.192	40.914	37.181	186.500	214.222	7.07E-02	0.100
26	3.715	0.931	20.026	39.382	32.396	170.403	196.401	6.64E-02	0.100
27	3.715	0.967	20.796	37.960	28.525	157.100	180.691	6.27E-02	0.099
28	3.715	0.999	21.491	36.639	25.348	145.600	167.193	5.95E-02	0.098
29	3.715	1.029	22.120	35.400	22.567	136.200	155.099	5.66E-02	0.097
30	3.715	1.056	22.710	34.252	20.457	126.000	144.295	5.40E-02	0.096
31	3.715	1.082	23.257	33.172	18.540	120.700	134.828	5.18E-02	0.096
22	2.715	1.105	23.766	32.164	16.899	114.300	126.923	4.97E-02	0.095
33	3.715	1.127	24.248	31.204	15.469	109.600	118.055	4.78E-02	0.094
34	2.715	1.148	24.684	30.305	14.217	103.500	110.917	4.61E-02	0.094
35	3.715	1.167	25.100	29.456	13.116	99.000	104.418	4.46E-02	0.093
36	2.715	1.188	25.490	28.654	12.141	94.800	98.482	4.32E-02	0.092

Table 4-10 Temperature rises on surface, asperities and lubricant film temperatures versus number of teeth for fine ground, load 50 hp , gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at maximum surface temperature

Np	mu	lambda	h	Vs	Ts	Tasp	Tfl	Tflasp
17	0 200	4 124	11 220	202 500	80 287	117 852	492 025	510 108
18	0 260	6 330	14.527	240 827	70 845	92 828	527 070	555 042
19	0 340	6.692	19 210	229 210	80 098	80 844	612 443	627 202
20	0 400	7 772	21 294	227 840	81 014	70 079	542 510	652 639
21	0 460	8 812	24 147	217 905	54 837	62 015	662 825	672 850
22	0 540	9 008	27 395	209 144	60 812	56 015	700 875	709 906
23	0 600	10 055	29 010	200 005	46 563	51 208	709 241	715 013
24	0 680	11 870	22 540	192 409	42 910	46 800	707 602	710 112
25	0 740	12 940	25 450	180 409	40 207	43 704	722 740	722 238
26	0 800	12 709	27 902	180 005	27 452	40 420	717 487	725 890
27	0 880	14 629	40 072	173 802	34.963	37 508	708 205	717 032
28	0 940	15 504	42 720	168 210	33 100	25 412	713 495	721 871
29	1 000	16 272	44 650	163 030	31 000	22 157	701 525	709 807
30	1 080	17 127	46 028	158 900	28.296	31 140	690 875	697 194
31	1 140	18 021	49 277	152 404	27 012	29 867	650 454	654 840
32	1 200	18 724	51 232	149 009	26 415	27 028	672 120	680 402
33	1 260	19 421	53 240	144 862	25 052	26 444	657 690	665 002
34	1 320	20 110	55 101	140 541	23 900	25 068	642 220	651 440
35	1 380	20 774	56 920	127 220	22 660	23 944	629 861	637 001
36	1 440	21 422	58 807	133 709	21 910	22 700	614 615	622 805

Table 4-11 Temperature rises on surface, asperities and lubricant film temperatures versus number of teeth for fine ground load 50 hp gear ratio Mg=5 center distance Cd=10 and constant oil viscosity at maximum surface temperature

Np	mu	lambda	h	Vs	Ts	Tasp	Tfl	Tflasp	Ac/Ao	f
17	0 200	1 251	3 636	114 824	64 023	525 000	187 982		8 28E-02	0 830
18	0 320	2.164	5 992	106 867	70 802	132 188	177 124	227 801		
19	0 440	2 095	8 182	183 302	58 510	88 867	191 472	220 332		
20	0 540	3 722	10 188	98 444	40 421	67 012	190 082	215 840		
21	0 600	4 602	12 334	94 825	42 859	56.188	200 820	221 882		
22	0 780	5.256	14 403	88 867	88 100	45.306	219 790	227 624		
22	0 882	5 881	16.224	88.263	35 802	42.134	221 238	228 428		
24	0 982	6 598	17 980	82 872	21 889	27 376	222 715	228 807		
25	1 002	7 101	19 703	79 722	28 806	33 581	223 255	228 280		
26	1 180	7 298	21 307	76 862	26.545	30 497	223 277	227 582		
27	1.280	6.369	22 985	74 002	24.526	27 881	222 588	226.401		
28	1 380	8 963	24 558	71 865	22 769	25 843	221 423	224 838		
29	1 480	9 450	25.917	69 280	21 884	23.691	217 055	220 188		
30	1.540	9 941	27.239	66 909	10 010	21 917	212.752	215 803		
31	1 622	10 411	28.527	64 928	18 211	20.270	208 521	211 104		
32	1 702	10 870	29.784	60 870	17 157	18.908	204 380	208 837		
33	1 780	11 318	31 011	61 148	16 128	17 700	200 295	208 010		
34	1 862	11 756	32.211	55 416	15 188	16.022	198 210	198 511		
35	1 928	12 121	33.212	57 702	14 206	15 582	190 656	192 841		
36	1 992	12 476	34 190	56.238	13.465	14 848	188 114	187 892		

Table 4-12 Temperature rises on surface asperities and lubricant film temperatures versus number of teeth for fine ground load 50 hp gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at maximum surface temperature

Np	mu	lambda	h	Va	Ts	Tasp	Tfs	Tfasp	Ac/Aa	f
17	0.160	0.427	1.165	28.410	92.480	1235.000	113.682		0.372	0.169
18	0.360	1.007	2.813	68.230	65.828	218.000	90.000		0.139	0.060
19	0.200	1.553	4.256	23.279	58.021	142.254	81.000	102.877		
20	0.050	2.004	5.058	56.766	42.000	81.074	81.302	130.413		
21	0.040	2.061	7.010	46.457	38.287	58.200	81.032	114.700		
22	0.050	3.014	8.260	46.322	31.500	47.308	81.031	106.438		
23	1.120	2.422	9.466	44.367	28.020	39.450	80.473	101.067		
24	1.200	2.863	10.830	42.570	25.175	33.018	80.056	96.510		
25	1.300	4.269	11.087	40.014	22.665	28.614	80.278	95.073		
26	1.500	4.044	12.725	39.382	20.500	25.259	80.710	93.264		
27	1.600	4.878	12.890	37.950	18.727	23.455	84.291	88.830		
28	1.700	2.303	4.030	30.838	17.183	21.158	82.000	85.286		
29	1.800	2.812	15.000	38.402	12.812	19.242	79.061	83.274		
30	1.900	8.997	16.240	34.282	14.642	17.821	78.030	80.896		
31	1.980	0.196	16.978	30.172	13.551	16.182	78.494	78.180		
32	2.000	0.450	17.630	22.158	12.284	14.907	73.142	72.466		
33	2.140	6.714	18.367	31.204	11.750	12.812	70.951	73.036		
34	2.250	8.084	19.080	30.305	10.206	12.840	68.981	70.764		
35	2.280	7.176	12.862	29.458	10.203	11.853	66.442	68.153		
36	2.388	7.414	20.318	28.654	8.984	11.166	64.961	66.225		

Table 4-13 Temperature rises on surface asperities and lubricant film temperatures versus number of teeth for rough ground load 50 hp gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at maximum surface temperature

Np	mu	lambda	h	Va	Ts	Tasp	Tfs	Tfasp	Ac/Aa	f
17	0.200	0.627	11.383	680.668	88.287	284.300	482.025		0.121	0.097
18	0.250	0.892	14.627	246.827	70.048	209.000	537.070		0.74E-02	0.002
19	0.340	0.852	16.310	228.210	66.688	178.000	612.643		7.54E-02	0.060
20	0.400	0.902	21.294	227.080	61.014	156.000	642.210		8.83E-02	0.080
21	0.460	1.123	24.147	217.000	54.027	144.000	680.835		4.42E-02	0.084
22	0.540	1.274	27.395	206.144	50.012	130.000	700.978		2.57E-02	0.082
23	0.600	1.396	30.010	200.000	46.583	128.000	690.241		2.62E-02	0.081
24	0.600	1.513	32.540	193.466	42.010	127.330	707.502	823.902		
25	0.740	1.648	28.486	186.450	40.287	109.076	720.746	823.010		
26	0.800	1.786	27.802	180.000	37.452	97.460	717.427	808.274		
27	0.860	1.884	40.072	173.000	34.903	78.017	709.398	784.125		
28	0.940	1.967	42.729	166.310	33.106	67.164	713.448	794.709		
29	1.000	2.080	44.856	160.030	31.054	60.209	701.535	778.597		
30	1.060	2.183	46.926	156.000	28.200	54.520	688.872	764.061		
31	1.140	2.287	48.377	153.404	27.212	49.666	680.454	761.536		
32	1.200	2.394	21.333	148.006	26.415	45.653	672.130	742.711		
33	1.260	2.476	53.240	144.662	25.853	42.402	627.090	720.960		
34	1.320	2.563	22.101	140.841	23.800	39.401	643.228	714.341		
35	1.380	2.647	55.620	137.229	22.668	36.786	628.061	695.877		
36	1.440	2.730	58.087	133.709	21.810	34.439	614.618	683.810		

Table 4-14 Temperature rises on surface, asperities and lubricant film temperatures versus number of teeth for rough ground, load 50 hp., gear ratio Mg= 5, center distance Cd=10 and constant oil viscosity at maximum surface temperature

Np	mu	lambda	h	Vs	Ts	Tasp	Tfs	Tfasp	Ac/Ao	f
17	0.269	0.186	2.538	114.924	94.023	347.800	167.462		0.186	0.123
18	0.269	0.275	5.802	109.667	75.562	396.000	177.124		0.186	0.114
19	0.443	0.361	8.182	103.302	68.516	292.000	181.472		0.140	0.108
20	0.360	0.474	10.186	98.444	48.431	292.000	186.042		0.186	0.104
21	0.560	0.574	12.334	94.025	43.650	168.000	200.000		0.112	0.100
22	0.780	0.670	14.483	89.967	39.120	171.000	219.200		9.00E-02	0.097
23	0.850	0.795	16.234	86.262	29.002	152.400	221.232		8.74E-02	0.095
24	0.882	0.837	17.909	82.872	21.883	139.846	222.715		7.71E-02	0.093
25	1.200	0.918	19.783	79.722	23.636	128.000	222.355		5.60E-02	0.091
26	1.180	0.968	21.917	76.853	29.545	119.400	223.277		6.06E-02	0.090
27	1.200	1.068	22.918	74.182	24.526	112.000	222.906		5.24E-02	0.088
28	1.360	1.142	24.559	71.685	22.759	107.000	221.429		4.66E-02	0.086
29	1.400	1.205	25.917	69.366	21.694	102.000	217.055		4.16E-02	0.087
30	1.540	1.267	27.239	66.996	19.818	97.600	212.752		3.72E-02	0.086
31	1.620	1.327	28.527	64.800	18.211	94.000	208.921		3.33E-02	0.085
32	1.700	1.385	29.784	62.870	17.157	91.000	204.360		2.99E-02	0.084
33	1.780	1.442	31.011	61.148	16.128	52.824	200.209	241.581		
34	1.860	1.498	32.211	59.418	15.138	48.038	196.210	232.914		
35	1.820	1.545	33.212	57.793	14.286	40.719	190.566	222.204		
36	1.880	1.590	34.108	56.250	13.455	38.458	185.114	212.538		

Table 4.15 Temperature rises on surface, asperities and lubricant film temperatures versus number of teeth for rough ground, load 50 hp., gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

Np	mu	lambda	h	Vs	Ts	Tasp	Tfs	Tfasp	Ac/Ao	f
17	0.180	0.054	1.169	88.416	68.660	1267.000	113.690		0.214	0.127
18	0.360	0.131	2.837	85.236	65.629	550.000	98.980		0.197	0.123
19	0.540	0.218	4.337	83.379	51.918	458.000	94.482		0.181	0.122
20	0.580	0.283	5.609	80.280	42.996	343.000	91.365		0.169	0.115
21	0.690	0.328	7.018	78.457	39.287	282.000	91.832		0.159	0.112
22	0.660	0.354	8.268	76.382	31.955	241.000	91.031		0.145	0.111
23	1.120	0.446	9.486	74.287	28.579	210.000	90.472		0.126	0.109
24	1.280	0.495	10.539	72.573	25.175	188.000	90.887		0.108	0.122
25	1.330	0.544	11.597	70.814	22.869	168.400	88.276		0.116	0.104
26	1.600	0.592	12.725	68.992	20.596	154.000	86.716		0.110	0.103
27	1.600	0.634	13.640	67.560	19.737	141.500	84.291		0.104	0.101
28	1.700	0.675	14.530	66.034	17.183	121.800	82.658		0.096	0.099
29	1.800	0.716	15.690	65.408	15.912	123.300	79.981		0.092	0.099
30	1.800	0.755	16.240	64.252	14.942	115.000	78.009		0.087	0.096
31	1.900	0.792	16.978	63.172	12.881	108.000	75.494		0.085	0.097
32	2.000	0.822	17.695	62.188	12.594	103.000	73.142		0.079	0.097
33	2.140	0.866	18.267	61.214	11.780	98.299	70.151		0.077	0.096
34	2.220	0.887	19.080	60.238	10.900	94.000	68.601		0.071	0.095
35	2.280	0.915	19.982	59.456	10.283	90.300	66.442		0.068	0.094
36	2.360	0.943	20.218	58.654	9.564	86.750	64.061		0.068	0.094

Table 4-16 Temperature rises on aspenties versus number of teeth and load for fine ground gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at inlet temperature

Np	Hp=10	Hp=20	Hp=30	Hp=40	Hp=50	Hp=60	Hp=70	Hp=80	Hp=90	Hp=100
17	404 123	404 123	404 123	404 123	404 123	404 123	404 123	404 123	404 123	404 123
18	299 186	299 186	299 186	299 186	299 186	299 186	299 186	299 186	299 186	299 186
19	234 841	234 841	234 841	234 841	234 841	234 841	234 841	234 841	234 841	234 841
20	191 518	191 318	191 518	191 318	191 318	191 518	191 318	191 318	191 518	191 318
21	160 261	160 261	160 261	160 261	160 261	160 261	160 261	160 261	160 261	160 261
22	136 717	136 717	136 717	136 717	136 717	136 717	136 717	136 717	136 717	136 717
23	118 415	118 413	118 413	118 415	118 413	118 415	118 415	118 415	118 416	118 413
24	103 815	103 813	103 813	103 813	103 813	103 815	103 813	103 813	103 816	103 813
25	91 932	91 932	91 932	91 932	91 932	91 932	91 932	91 932	91 932	91 932
26	82 068	82 068	82 068	82 068	82 068	82 068	82 068	82 068	82 068	82 068
27	73 846	73 846	73 846	73 846	73 846	73 846	73 846	73 846	73 846	73 846
28	66 841	66 841	66 841	66 841	66 841	66 841	66 841	66 841	66 841	66 841
29	60 832	60 832	60 832	60 832	60 832	60 832	60 832	60 832	60 832	60 832
30	55 633	55 633	55 633	55 633	55 633	55 633	55 633	55 633	55 633	55 633

Table 4-17 Temperature rises on aspenties versus number of teeth and load for fine ground gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	924 003	924 002	924 002	924 002	924 002	924 003	924 003	924 002	924 002	924 002
18	693 505	693 505	693 505	693 505	693 505	693 505	693 505	693 505	693 505	693 505
19	179 290	179 290	179 290	179 290	179 290	179 290	179 290	179 290	179 290	179 290
20	124 078	124 078	124 078	124 078	124 078	124 078	124 078	124 078	124 078	124 078
21	93 813	93 813	93 813	93 813	93 813	93 813	93 813	93 813	93 813	93 813
22	74 137	74 137	74 137	74 137	74 137	74 137	74 137	74 137	74 137	74 137
23	59 963	59 963	59 963	59 963	59 963	59 963	59 963	59 963	59 963	59 963
24	50 828	50 828	50 828	50 828	50 828	50 828	50 828	50 828	50 828	50 828
25	43 366	43 366	43 366	43 366	43 366	43 366	43 366	43 366	43 366	43 366
26	37 534	37 534	37 534	37 534	37 534	37 534	37 534	37 534	37 534	37 534
27	32 869	32 869	32 869	32 869	32 869	32 869	32 869	32 869	32 869	32 869
28	29 068	29 068	29 068	29 068	29 068	29 068	29 068	29 068	29 068	29 068
29	25 916	25 916	25 916	25 916	25 916	25 916	25 916	25 916	25 916	25 916
30	23 273	23 273	23 273	23 273	23 273	23 273	23 273	23 273	23 273	23 273

Table 4-18 Temperature rises on asperities versus number of teeth and load for rough ground, gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at inlet temperature

Ng	HP=10	HP=30	HP=50	HP=70	HP=90	HP=110	HP=130	HP=150	HP=170	HP=190
17	688 134	688 134	688 134	688 134	688 134	688 134	688 134	688 134	688 134	688 134
18	467 997	467 997	467 997	467 997	467 997	467 997	467 997	467 997	467 997	467 997
19	350 977	350 977	350 977	350 977	350 977	350 977	350 977	350 977	350 977	350 977
20	276 155	276 155	276 155	276 155	276 155	276 155	276 155	276 155	276 155	276 155
21	225 830	225 830	225 830	225 830	225 830	225 830	225 830	225 830	225 830	225 830
22	189 836	189 836	189 836	189 836	189 836	189 836	189 836	189 836	189 836	189 836
23	161 406	161 406	161 406	161 406	161 406	161 406	161 406	161 406	161 406	161 406
24	139 876	139 876	139 876	139 876	139 876	139 876	139 876	139 876	139 876	139 876
25	122 683	122 683	122 683	122 683	122 683	122 683	122 683	122 683	122 683	122 683
26	108 680	108 680	108 680	108 680	108 680	108 680	108 680	108 680	108 680	108 680
27	97 056	97 056	97 056	97 056	97 056	97 056	97 056	97 056	97 056	97 056
28	87 355	87 355	87 355	87 355	87 355	87 355	87 355	87 355	87 355	87 355
29	79 061	79 061	79 061	79 061	79 061	79 061	79 061	79 061	79 061	79 061
30	72 693	72 693	73 008	72 693	72 693	72 693	72 693	72 693	72 702	72 693

Table 4-19 Temperature rises on asperities versus number of teeth and load for rough ground gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

Ng	HP=10	HP=30	HP=50	HP=70	HP=90	HP=110	HP=130	HP=150	HP=170	HP=190
17	1441 900	3422 463	3284 778	4076 763	4618 274	5524 303	6201 356	6454 896	7467 656	8103 354
18	894 806	1186 510	1583 802	1965 181	2323 204	2963 026	2886 884	3305 044	3610 287	3967 148
19	491 000	625 760	1119 338	1388 758	1641 757	1832 326	2113 027	2335 663	2551 511	2758 000
20	371 200	523 845	845 997	1049 346	1240 513	1422 307	1596 849	1764 783	1927 723	2086 846
21	338 500	518 833	760 228	873 573	1031 523	1182 084	1327 635	1467 482	1603 013	734 983
22	284 000	443 883	601 790	748 700	852 737	1013 096	1136 128	1255 803	1371 764	1484 581
23	231 500	399 335	437 706	654 781	774 057	887 405	995 304	1100 308	1303 800	1301 823
24	206 480	347 133	473 450	583 787	696 149	781 287	888 365	981 804	1073 465	1160 372
25	188 800	313 984	435 138	527 802	623 662	714 977	802 805	887 148	968 132	1048 767
26	179 480	288 577	388 438	481 884	566 787	653 255	733 316	810 584	888 424	856 250
27	167 180	264 218	358 111	444 348	525 296	602 228	676 093	747 288	818 318	883 436
28	145 800	245 208	330 352	413 385	487 513	558 647	627 453	693 546	757 589	818 894
29	136 500	228 960	316 469	388 232	455 413	522 164	586 188	647 892	707 716	766 868
30	128 000	315 280	881 777	362 606	437 868	496 708	559 856	595 874	663 168	718 797

Table 4-20 Temperature rises on aspenties versus number of teeth and load for fine ground, gear ratio M_G=2, center distance Cd=10 and constant oil viscosity at maximum surface temperature

Np	HP=15	HP=30	HP=20	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	117.852	117.852	117.852	117.852	117.852	117.852	117.852	117.852	117.852	117.852
18	83.638	83.638	83.638	83.638	83.638	83.638	83.638	83.638	83.638	83.638
19	60.844	60.844	60.844	60.844	60.844	60.844	60.844	60.844	60.844	60.844
20	70.078	70.078	70.078	70.078	70.078	70.078	70.078	70.078	70.078	70.078
21	62.010	62.010	62.010	62.010	62.010	62.010	62.010	62.010	62.010	62.010
22	56.010	56.010	56.010	56.010	56.010	56.010	56.010	56.010	56.010	56.010
25	51.309	51.309	51.309	51.309	51.309	51.309	51.309	51.309	51.309	51.309
24	48.899	48.899	48.899	48.899	48.899	48.899	48.899	48.899	48.899	48.899
25	43.784	45.784	43.784	43.784	45.784	45.784	43.784	43.784	43.784	45.784
26	40.429	40.429	40.429	40.429	40.429	40.429	40.429	40.429	40.429	40.429
27	37.569	37.569	37.569	37.569	37.569	37.569	37.569	37.569	37.569	37.569
28	35.415	35.415	35.413	35.415	35.415	35.415	35.413	35.415	35.415	35.415
29	33.157	33.157	33.157	33.157	33.157	33.157	33.157	33.157	33.157	33.157
30	31.148	31.148	31.148	31.148	31.148	31.148	31.148	31.148	31.148	31.148

Table 4-21 Temperature rises on aspenties versus number of teeth and load for fine ground, gear ratio M_G=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

Np	HP=15	HP=30	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	1935.599	1740.899	2359.290	2937.422	3489.731	3967.937	4454.140	4923.517	5378.818	5820.253
18	818.898	871.188	1182.785	1465.195	1752.837	1845.835	2238.222	2484.037	2891.867	2912.624
19	142.254	142.254	142.254	142.254	142.254	142.254	142.254	142.254	142.254	142.254
20	81.674	81.674	81.674	81.674	81.674	81.674	81.674	81.674	81.674	81.674
21	59.599	59.599	59.599	59.599	59.599	59.599	59.599	59.599	59.599	59.599
22	47.508	47.508	47.508	47.508	47.508	47.508	47.508	47.508	47.508	47.508
23	39.459	39.459	39.459	39.459	39.459	39.459	39.459	39.459	39.459	39.459
24	33.918	33.918	33.918	33.918	33.918	33.918	33.918	33.918	33.918	33.918
25	29.814	29.814	29.814	29.814	29.814	29.814	29.814	29.814	29.814	29.814
26	26.259	26.259	26.259	26.259	26.259	26.259	26.259	26.259	26.259	26.259
27	23.455	23.455	23.455	23.455	23.455	23.488	23.455	23.455	23.455	23.455
28	21.159	21.159	21.159	21.159	21.159	21.159	21.159	21.159	21.159	21.159
29	19.243	19.243	19.245	19.245	19.243	19.346	19.243	19.243	19.243	19.243
30	17.621	17.621	17.621	17.621	17.621	17.621	17.621	17.621	17.621	17.621

Table 4-22 Temperature rises on asperities versus number of teeth and load for rough ground, gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at maximum surface temperature

Hp	Hp=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	264 000	443 893	601 790	788 706	882 737	1013 [illegible]	1139 120	1355 903	1371 784	1484 881
18	209 000	351 495	478 417	591 141	698 834	801 335	892 436	994 177	1065 890	1175 296
19	179 000	299 358	408 752	503 480	595 170	680 381	760 098	848 715	924 815	1000 980
20	158 000	265 723	360 182	446 551	529 305	605.718	678 958	751 579	820 899	888 499
21	144 000	242 175	328 349	407 364	481.493	552 047	618 708	686 883	749 248	809 772
22	130 000	220 724	318 013	384 666	454 743	521.378	585 278	648 828	706 677	764 764
23	135 000	215 299	301 777	269 030	427 [illegible]	490 706	550 [illegible]	608 574	665 100	718 787
24	127 330	137 330	127 330	127 330	127 320	127 330	137 330	127 330	137 330	137 330
25	103 070	103 078	103 078	103 078	103 075	103 078	103 078	103 076	103 078	103 070
26	87 480	87.480	87.480	87 460	87 439	87 480	87 880	87 455	87 468	87 880
27	76 017	76 017	76 817	79 817	78 017	76 017	76 817	76 017	76 017	76 017
28	67 164	67 164	67 164	87 164	67 164	87 164	67 164	67 164	87 164	67 164
29	60 209	60.209	60.209	60 209	60 209	60.209	60.209	60.209	60 209	60.209
30	54 520	54.520	54 520	64 520	64 520	54 520	54 520	54 520	54 520	54 520

Table 4-23 Temperature rises on asperities versus number of teeth and load for rough ground, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

Hp	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	1387 000	2333 647	3181 878	3923.028	4637 714	5317 285	5968 970	6587 721	7207 863	7799 874
18	859 000	1[illegible]06 301	1903 165	1863 833	2203 499	2526 381	2836 018	3134 764	3434 284	3705 830
19	459 000	771 643	1046 284	1299 248	1534 759	1759 645	1975 314	2183 384	2385 034	2581 147
20	343 000	576 855	781 871	978 151	1148 000	1314 645	1476 100	1631 592	1782 380	1528 831
21	288 000	474 280	642 801	797 618	943 924	1081 693	1313 503	1341 426	1465 315	1585 603
22	241 000	405 312	549 381	681 651	805 832	923 013	1037 148	1148 396	1253 273	1356 243
23	318 000	363 176	479 690	593 075	702 177	805 000	903 738	906 834	1001 100	1100 017
34	188 000	313 813	423 880	526 887	631 928	713 061	803 454	884 770	960 464	1045 065
25	188 400	283 314	383 000	476 307	563 070	645 585	724 713	80[illegible] 850	875 032	946.983
26	154 000	380 990	351 044	436 578	514 830	289 383	662 743	733 552	800 287	860 066
37	141 000	237 133	321 410	398 908	471 499	540 545	600 796	670 713	732.657	792 601
28	131 000	331 164	289 764	371 838	439 687	504 128	566 813	635 523	683.294	738 470
29	123 000	300 651	280 370	347 807	411 275	471 640	530 333	585 990	636 127	691 000
30	115 000	183 406	262 143	325.209	384 828	440 871	494 000	547 036	597 000	646 583

Table 4-24 Factor K versus number of teeth and load for rough ground and 4340 high carbon steel gear gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at inlet temperature

	K(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	4.023831	2.011915632	1.34121	1.005908	0.804725	0.670605	0.578804	0.502854	0.447707	0.402383
18	2.379186	1.189592988	0.793062	0.594840	0.475237	0.396831	0.339455	0.297003	0.264071	0.237616
19	1.574606	0.787302872	0.524868	0.39365	0.314921	0.262434	0.224944	0.196826	0.178050	0.15748
20	1.114461	0.557304044	0.371537	0.275652	0.222877	0.185768	0.15923	0.139329	0.123840	0.111461
21	0.828104	0.417052218	0.278781	0.208470	0.164071	0.15755	0.117730	0.103013	0.091067	0.082841
22	0.600732	0.318365022	0.200577	0.157185	0.125784	0.104749	0.089810	0.07859	0.069855	0.062873
23	0.491362	0.245680854	0.163778	0.12283	0.098264	0.081887	0.070180	0.061415	0.054591	0.049132
24	0.391361	0.195680488	0.130454	0.09784	0.078272	0.065227	0.055900	0.04907	0.043485	0.039136
25	0.300686	0.150343148	0.100562	0.075173	0.060137	0.052781	0.045281	0.039586	0.033387	0.031867
26	0.240045	0.120022005	0.080582	0.060071	0.051937	0.043201	0.037086	0.032451	0.028854	0.025900
27	0.215385	0.107807398	0.071785	0.053848	0.043077	0.035898	0.030769	0.026923	0.023932	0.021539
28	0.180470	0.090232	0.060143	0.045107	0.036088	0.030071	0.025775	0.022554	0.020048	0.018043
29	0.152476	0.07623806	0.050825	0.038110	0.030495	0.025413	0.021782	0.01906	0.016942	0.015248
30	0.129866	0.064933086	0.043289	0.032466	0.025973	0.021644	0.018552	0.016233	0.01443	0.012987

Table 4-25 Factor K versus number of teeth and load for rough ground and 4340 high carbon steel gear gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

	K(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	1.280107	1.700008471	2.092007	2.410334	2.701644	2.950393	3.19051	3.417213	3.624587	3.82058
18	0.654336	0.901939783	1.107825	1.335071	1.552582	1.700758	1.837039	1.963870	2.083007	2.105682
19	0.530537	0.750262201	0.914017	1.001078	1.106510	1.290544	1.403668	1.500685	1.59101	1.677705
20	0.320895	0.56120481	0.687443	0.75378	0.857484	0.97218	1.050086	1.122589	1.196806	1.255082
21	0.332664	0.47901075	0.575780	0.665069	0.744575	0.815641	0.880093	0.941022	0.998555	1.052889
22	0.282678	0.380761823	0.489646	0.585348	0.632070	0.692404	0.747880	0.799524	0.848023	0.893605
23	0.24452	0.345802507	0.42337	0.488039	0.546707	0.598948	0.646930	0.691606	0.733051	0.773239
24	0.214084	0.30277837	0.370827	0.428188	0.478770	0.524422	0.56644	0.60555	0.642283	0.677025
25	0.18957	0.268092094	0.328348	0.378139	0.423881	0.464340	0.501554	0.536184	0.568700	0.599477
26	0.1696	0.239850051	0.293758	0.3397	0.379234	0.415434	0.44872	0.479707	0.508801	0.536323
27	0.153065	0.216466796	0.265117	0.30613	0.343264	0.374031	0.404877	0.432934	0.459105	0.484034
28	0.138943	0.196485281	0.240657	0.277886	0.310686	0.34034	0.367600	0.392991	0.416820	0.439377
29	0.127008	0.179016328	0.219254	0.254014	0.283994	0.311105	0.336031	0.359233	0.381028	0.401834
30	0.116917	0.16533892	0.202458	0.233825	0.261428	0.286378	0.309321	0.330678	0.350737	0.369789

Table 4-26 Factor K versus number of teeth and load for fine ground and 4340 high carbon steel gear, gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at inlet temperature

	K(4340 High hardness Steel)								
Ng	HP=10	HP=20	HP=30	HP=40	HP=50	HP=70	HP=80	HP=90	HP=100
17	1.390931	0.696946	0.46663	0.349973	0.279878	0.233319	0.199884	0.174964	0.155543	0.139958
18	0.87114	0.48557	0.333713	0.242765	0.194228	0.161857	0.138734	0.121392	0.107904	0.097114
19	0.790163	0.3945	0.2363	0.226397	0.172296	0.141838	0.119199	0.101313	0.088648	0.078799	0.07091
20	0.53509	0.268045	0.178697	0.134023	0.107218	0.089348	0.076584	0.067011	0.059588	0.053609
21	0.415768	0.207854	0.1385	0.103927	0.083142	0.069285	0.059387	0.051993	0.04618	0.041571
22	0.328869	0.164435	0.109623	0.082217	0.065774	0.054819	0.046987	0.041105	0.036541	0.032887
23	0.264405	0.132225	0.08815	0.066113	0.05289	0.044075	0.037779	0.033056	0.029383	0.02644
24	0.215583	0.107787	0.071861	0.053896	0.043117	0.035931	0.03079	0.026948	0.023954	0.021556
25	0.1772	0.088612	0.059074	0.044456	0.035565	0.029637	0.025403	0.022228	0.019758	0.017782
26	0.1481	0.074054	0.049366	0.037047	0.029637	0.024698	0.02117	0.018523	0.016465	0.014819
27	0.124613	0.062308	0.041537	0.031153	0.024923	0.020769	0.017802	0.015578	0.013849	0.012461
28	0.106436	0.052818	0.035213	0.026408	0.021127	0.017606	0.015091	0.013204	0.01173	0.010564
29	0.092202	0.045161	0.030067	0.02255	0.018042	0.015034	0.012882	0.011275	0.010022	0.009022
30	0.077531	0.038765	0.025844	0.019382	0.015505	0.012923	0.011078	0.009691	0.008615	0.007753

Table 4-27 Factor K versus number of teeth and load for fine ground and 4340 high carbon steel gear, gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

	K(4340 High hardness Steel)								
Ng	HP=10	HP=20	HP=30	HP=40	HP=50	HP=70	HP=80	HP=90	HP=100
17	0.486755	0.243379	0.162586	0.12419	0.099352	0.082793	0.070995	0.062095	0.055183	0.049676
18	0.131818	0.065909	0.043972	0.032934	0.026324	0.021939	0.018805	0.016452	0.014624	0.013162
19	0.099863	0.049977	0.033318	0.017444	0.013991	0.011658	0.009993	0.008744	0.007773	0.006999
20	0.044964	0.022199	0.014797	0.011088	0.008878	0.007398	0.006343	0.005549	0.004932	0.004439
21	0.030661	0.01533	0.01022	0.007666	0.006133	0.00511	0.00438	0.003833	0.003407	0.003066
22	0.022298	0.011149	0.007431	0.005572	0.004458	0.003715	0.003185	0.002789	0.002477	0.002229
23	0.01679	0.008395	0.005597	0.004198	0.003358	0.002798	0.002399	0.002099	0.001866	0.001679
24	0.012884	0.006442	0.004295	0.003346	0.002577	0.002164	0.001855	0.001623	0.001443	0.001298
25	0.01005	0.005025	0.003417	0.002562	0.00205	0.001708	0.001464	0.001281	0.001138	0.001025
26	0.008208	0.004114	0.002743	0.002057	0.001646	0.001371	0.001176	0.001029	0.000914	0.000823
27	0.0047	0.00235	0.002233	0.001675	0.00134	0.001117	0.000957	0.000838	0.000744	0.00067
28	0.005522	0.002761	0.001841	0.00138	0.001104	0.00092	0.000789	0.00069	0.000614	0.000552
29	0.004558	0.002279	0.001533	0.00115	0.00092	0.000768	0.000657	0.000575	0.000511	0.00046
30	0.003694	0.001933	0.001288	0.000966	0.000773	0.000644	0.000552	0.000483	0.000429	0.000387

Table 4-28 Factor K versus number of teeth and load for rough ground and 1020 low carbon steel gear gear ratio Mg−2, center distance Cd−10 and constant oil viscosity at inlet temperature

	K(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	1.534218	0.767107169	0.5118	0.383554	0.306842	0.255772	0.219273	0.191777	0.170499	0.153423
18	0.806402	0.4029620	0.26874	0.20151	0.161264	0.134387	0.115203	0.100771	0.089584	0.080604
19	0.665368	0.3261881845	0.2201222	0.1651	0.12908	0.1030864	0.0857771	0.075205	0.0667711	0.06064
20	0.529972	0.2125479858	0.1416981	0.10625	0.085	0.0708534	0.0607215	0.053125	0.0472222	0.0425
21	0.314232	0.157115903	0.10474	0.078558	0.062848	0.0523732	0.04489	0.039278	0.0349158	0.031423
22	0.218726	0.1108877668	0.0739152	0.055384	0.0443047	0.0369166	0.0316428	0.0276957	0.0246187	0.0221578
23	0.187342	0.0936770766	0.0624487	0.046836	0.0374868	0.0312294	0.0267663	0.0234118	0.0208161	0.0187334
24	0.149228	0.0748112167	0.04974.2	0.037307	0.0298446	0.0248711	0.0213213	0.0186562	0.0165841	0.0149223
25	0.120752	0.0602778362	0.040151	0.030168	0.0241491	0.0201125	0.01725	0.0150834	0.0134117	0.0120759
26	0.098018	0.0489529108	0.0326096	0.0244755	0.0195804	0.0163042	0.0139845	0.0122377	0.0108823	0.0097901
27	0.082127	0.0410813442	0.0273766	0.0205352	0.0164265	0.0136869	0.0117352	0.0102666	0.0091295	0.0082212
28	0.069758	0.0348387871	0.0232033	0.0174095	0.0139278	0.0116068	0.0099538	0.0087044	0.0077444	0.0069708
29	0.059128	0.0295128053	0.01968	0.0147635	0.0118128	0.0098418	0.0084386	0.0073824	0.0065688	0.0059118
30	0.043818	0.0218758911	0.0145836	0.0109378	0.0087504	0.0072918	0.0062501	0.0054689	0.0048612	0.0043751

Table 4-29 Factor K versus number of teeth and load for rough ground and 1020 low carbon steel gear gear ratio Mg−10, center distance Cd−10 and constant oil viscosity at inlet temperature

	K(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.496675	0.25 0.03277	0.7871 12	0.125251	0.100181	0.08418	0.071932	0.062887	0.055899	0.050303
18	0.264751	0.1344118188	0.456452	0.0674502	0.0539011	0.045304	0.0386864	0.0338184	0.0300742	0.0270716
19	0.202284	0.2850857 82	0.2563184	0.0404898	0.0452344	0.0195518	0.03522	0.0272176	0.0300842	0.03871
20	0.151335	0.2160522064	0.2361222	0.0425973	0.0358308	0.0270657	0.0402389	0.0220444	0.0454088	0.0765648
21	0.09907	0.1795587234	0.2189 18	0.2538344	0.2533807	0.2511005	0.2505024	0.2551117	0.3889502	0.4115506
22	0.1077294	0.1924223564	0.1800987	0.2155061	0.2491932	0.2504198	0.2496137	0.2504559	0.3233252	0.3405642
23	0.0932351	0.1315154978	0.1811859	0.1856471	0.2084651	0.2283835	0.2466925	0.2635731	0.2797737	0.2945357
24	0.0818634	0.1154483722	0.1412185	0.1632616	0.1825454	0.1989962	0.2158844	0.2309881	0.2448802	0.25815
25	0.0722653	0.1022237371	0.1259018	0.1448096	0.16182	0.1777657	0.1912443	0.2044448	0.2163448	0.2268576
26	0.0639018	0.09035538	0.112 11	0.1283337	0.1434604	0.1574409	0.1701327	0.1822111	0.1845259	0.2049
27	0.0569394	0.0805286967	0.1011888	0.1157725	0.105	0.1426982	0.1544418	0.1658715	0.1758952	0.1848802
28	0.052978	0.0749022842	0.0937782	0.1083558	0.1218465	0.1287772	0.1410717	0.1493848	0.1589277	0.1675535
29	0.0484268	0.0684875577	0.08568	0.0990636	0.1092288	0.1156624	0.1261229	0.1360876	0.1474889	0.1551444
30	0.0445781	0.0630043888	0.0778212	0.0895158	0.0996681	0.1091985	0.1172444	0.1268186	0.1337385	0.1410697

Table 4-30 Factor K versus number of teeth and load for fine ground and 1020 low carbon steel gear_gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at inlet temperature

	K(1020 low hardness Steel)									
No	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.33378	0.28685	0.177927	0.173445	0.106756	0.098963	0.078754	0.064777	0.059309	0.053378
18	0.370297	0.169148	0.173432	0.082574	0.074659	0.061715	0.0529	0.048287	0.041144	0.03707
19	0.278415	0.133208	0.090138	0.087694	0.054963	0.045908	0.038671	0.033977	0.030048	0.027042
20	0.204411	0.162206	0.08137	0.151153	0.040152	0.034703	0.029502	0.026551	0.022712	0.020441
21	0.15851	0.075255	0.057837	0.078127	0.031702	0.026418	0.022544	0.014514	0.017017	0.015851
22	0.175338	0.062899	0.041798	0.03136	0.02508	0.0209	0.017914	0.015675	0.013977	0.01254
23	0.100835	0.050416	0.033612	0.025208	0.020167	0.016806	0.014435	0.012604	0.011204	0.010084
24	0.082227	0.041101	0.027401	0.020551	0.01644	0.0137	0.011743	0.010275	0.009134	0.008222
25	0.067804	0.033902	0.022601	0.016951	0.013561	0.011301	0.009692	0.008476	0.007534	0.00678
26	0.056584	0.028257	0.018835	0.014126	0.011301	0.009417	0.007972	0.007063	0.006278	0.00565
27	0.047515	0.023757	0.015838	0.011879	0.009503	0.007918	0.006788	0.005939	0.005279	0.004751
28	0.040079	0.020036	0.013426	0.01007	0.008056	0.006717	0.005754	0.005035	0.004475	0.004028
29	0.034384	0.017187	0.011455	0.008588	0.006875	0.005732	0.004913	0.004299	0.003822	0.003439
30	0.029603	0.014799	0.009864	0.007397	0.005918	0.004987	0.004229	0.003699	0.003288	0.002958

Table 4-31 Factor K versus number of teeth and load for fine ground and 1020 low carbon steel gear_gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at inlet temperature

	K(1020 low hardness Steel)									
No	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.189414	0.094707	0.063138	0.047354	0.037883	0.031569	0.027064	0.023677	0.021048	0.018941
18	0.050188	0.025093	0.016728	0.012546	0.010037	0.008364	0.00717	0.006273	0.005576	0.005018
19	0.326873	0.013337	0.008891	0.006668	0.005335	0.004448	0.00381	0.003334	0.002964	0.002667
20	0.018027	0.009013	0.006007	0.004232	0.003383	0.002821	0.002418	0.002116	0.001881	0.001693
21	0.011491	0.005745	0.003831	0.002873	0.002298	0.001949	0.00167	0.001461	0.001299	0.001169
22	0.0065	0.00425	0.002833	0.002125	0.0017	0.001417	0.001214	0.001062	0.000944	0.00085
23	0.005492	0.002391	0.001594	0.001561	0.001195	0.001087	0.000915	0.0008	0.000711	0.00064
24	0.004861	0.002475	0.00165	0.001238	0.00099	0.000825	0.000707	0.000619	0.00055	0.000495
25	0.003968	0.001954	0.001303	0.000977	0.000782	0.000651	0.000558	0.000488	0.000434	0.000391
26	0.003138	0.001569	0.001046	0.000784	0.000628	0.000527	0.000448	0.000392	0.000348	0.000314
27	0.002555	0.001277	0.000857	0.000638	0.000511	0.000428	0.000365	0.000319	0.000284	0.000256
28	0.002109	0.001053	0.000707	0.000529	0.000421	0.000351	0.000301	0.000263	0.000234	0.000211
29	0.001753	0.000877	0.000584	0.000438	0.000351	0.000292	0.00025	0.000219	0.000195	0.000175
30	0.001474	0.000737	0.000491	0.000368	0.000295	0.000246	0.000211	0.000184	0.000164	0.000147

Table 4-32 Factor K versus number of teeth and load for rough ground and 4340 high carbon steel gear gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at maximum surface temperature

	K(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.557413	0.94487	1.03475	1.104827	1.335557	1.463358	1.580407	1.68974	1.78224	1.890107
18	0.4739	0.670196	0.820810	0.9478	1.059673	1.160813	1.253821	1.340302	1.4217	1.498603
19	0.407085	0.575705	0.705092	0.81417	0.91027	0.997151	1.077040	1.151411	1.221256	1.287310
20	0.364864	0.515995	0.631962	0.729727	0.81586	0.89373	0.965330	1.03196	1.094591	1.1538
21	0.335671	0.47471	0.581399	0.671341	0.750582	0.822222	0.888101	0.94942	1.007012	1.061484
22	0.325428	0.460225	0.563656	0.650856	0.72768	0.797133	0.861002	0.92045	0.976285	1.029094
23	0.309997	0.438398	0.535155	0.617994	0.690930	0.756885	0.817520	0.873975	0.926991	0.977134
24	0.324304	0.162152	0.108101	0.081076	0.064861	0.054051	0.046329	0.040538	0.036034	0.03243
25	0.223548	0.111774	0.074516	0.055887	0.04471	0.037258	0.031935	0.027944	0.024839	0.022355
26	0.168290	0.084145	0.056096	0.042072	0.033658	0.028048	0.024041	0.021036	0.018699	0.016829
27	0.132044	0.066022	0.044015	0.033011	0.026409	0.022007	0.018863	0.016506	0.014672	0.013204
28	0.106661	0.05333	0.035554	0.026665	0.021332	0.017777	0.015237	0.013333	0.011851	0.010666
29	0.088362	0.044181	0.029454	0.022091	0.017672	0.014727	0.012623	0.011045	0.009818	0.008836
30	0.07446	0.03723	0.02482	0.018616	0.014892	0.01241	0.010637	0.009307	0.008273	0.007446

Table 4-33 Factor K versus number of teeth and load for rough ground and 4340 high carbon steel gear gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at maximum surface temperature

	K(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	1.118314	1.582040	1.936709	2.236628	2.502863	2.741745	2.961427	3.165858	3.357943	3.539582
18	0.624627	0.883356	1.081865	1.249254	1.396708	1.530017	1.652607	1.766711	1.87388	1.975243
19	0.463637	0.655681	0.803042	0.927274	1.036723	1.135674	1.226660	1.311383	1.39091	1.466140
20	0.339247	0.479769	0.587593	0.678494	0.75858	0.830982	0.897563	0.959536	1.017741	1.072794
21	0.278235	0.393483	0.481517	0.55647	0.622152	0.681533	0.73614	0.786967	0.834705	0.879850
22	0.235606	0.333141	0.408012	0.471132	0.526742	0.577016	0.623240	0.666281	0.706698	0.744925
23	0.20121	0.284554	0.346506	0.402421	0.44992	0.492863	0.532352	0.569109	0.603631	0.636283
24	0.173865	0.245882	0.301143	0.347729	0.388773	0.42588	0.460003	0.491764	0.521594	0.549808
25	0.154559	0.21858	0.267705	0.309118	0.345605	0.378592	0.408926	0.43716	0.463678	0.48876
26	0.138525	0.195904	0.239933	0.27705	0.309752	0.339319	0.366503	0.391806	0.415576	0.438055
27	0.1233	0.174372	0.213561	0.246599	0.275707	0.302021	0.32622	0.348744	0.369899	0.389908
28	0.113028	0.159841	0.195765	0.22605	0.252731	0.276853	0.299035	0.319682	0.339074	0.357416
29	0.103583	0.146488	0.17941	0.207165	0.231618	0.253725	0.274054	0.292976	0.310748	0.327557
30	0.09437	0.13346	0.163454	0.188741	0.211016	0.231159	0.249681	0.26692	0.283111	0.298425

Table 4-34 Factor K versus number of teeth and load for fine ground and 4340 high carbon steel gear, gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at maximum surface temperature

	K(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.119052	0.059526	0.039684	0.029763	0.02381	0.019842	0.017007	0.014882	0.013228	0.011905
18	0.095126	0.047563	0.031709	0.023781	0.019025	0.015854	0.013589	0.011891	0.01057	0.009513
19	0.083974	0.041987	0.027991	0.020993	0.016795	0.013996	0.011996	0.010497	0.00933	0.008397
20	0.071775	0.035888	0.023925	0.017944	0.014355	0.011962	0.010254	0.008972	0.007975	0.007178
21	0.062264	0.031132	0.020755	0.015566	0.012453	0.010377	0.008895	0.007783	0.006918	0.006226
22	0.056402	0.028201	0.018801	0.0141	0.01128	0.0094	0.008057	0.00705	0.006267	0.00564
23	0.04965	0.024825	0.01655	0.012412	0.00993	0.008275	0.007093	0.006206	0.005517	0.004965
24	0.043998	0.021999	0.014666	0.010999	0.0088	0.007333	0.006285	0.0055	0.004889	0.0044
25	0.040188	0.020094	0.013396	0.010047	0.008038	0.006698	0.005741	0.005024	0.004465	0.004019
26	0.035921	0.017961	0.011974	0.00898	0.007184	0.005987	0.005132	0.00449	0.003991	0.003592
27	0.032252	0.016126	0.010751	0.008063	0.00645	0.005375	0.004607	0.004031	0.003584	0.003225
28	0.029652	0.014826	0.009884	0.007413	0.00593	0.004942	0.004236	0.003707	0.003295	0.002965
29	0.026798	0.013399	0.008933	0.0067	0.00536	0.004466	0.003828	0.00335	0.002978	0.00268
30	0.024303	0.012152	0.008101	0.006076	0.004861	0.004051	0.003472	0.003038	0.0027	0.00243

Table 4-35 Factor K versus number of teeth and load for fine ground and 4340 high carbon steel gear, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

	K(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.623275	0.881444	1.079544	1.24655	1.393686	1.526706	1.649031	1.762884	1.869825	1.970958
18	0.385927	0.545780	0.668452	0.771854	0.862967	0.945333	1.021077	1.091577	1.157781	1.22042
19	0.044533	0.022266	0.014844	0.011132	0.008907	0.007422	0.006362	0.005567	0.004948	0.004453
20	0.019235	0.009618	0.006412	0.004809	0.003847	0.003206	0.002748	0.002404	0.002137	0.001924
21	0.01239	0.006195	0.00413	0.003098	0.002478	0.002065	0.00177	0.001549	0.001377	0.001239
22	0.009077	0.004538	0.003026	0.002269	0.001815	0.001512	0.001297	0.001135	0.001009	0.000908
23	0.007104	0.003552	0.002368	0.001776	0.001421	0.001184	0.001015	0.000888	0.000789	0.00071
24	0.005782	0.002891	0.001927	0.001445	0.001156	0.000964	0.000826	0.000723	0.000642	0.000578
25	0.00478	0.00239	0.001593	0.001195	0.000956	0.000797	0.000683	0.000597	0.000531	0.000478
26	0.004028	0.002014	0.001343	0.001007	0.000806	0.000671	0.000575	0.000504	0.000448	0.000403
27	0.003412	0.001706	0.001137	0.000853	0.000682	0.000569	0.000487	0.000427	0.000379	0.000341
28	0.002926	0.001463	0.000975	0.000732	0.000585	0.000488	0.000418	0.000366	0.000325	0.000293
29	0.002535	0.001268	0.000845	0.000634	0.000507	0.000423	0.000362	0.000317	0.000282	0.000254
30	0.002218	0.001109	0.000739	0.000554	0.000442	0.000369	0.000317	0.000277	0.000246	0.000222

Table 4-36 Factor K versus number of teeth and load for rough ground and 1020 low carbon steel gear, gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at maximum surface temperature

	K(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.227794	0.39215	0.564551	0.455984	0.553364	0.55786	0.6826837	0.6443	0.6823631	0.7213349
18	0.199099	0.255946	0.312879	0.3612877	0.4540454	0.4422618	0.4790885	0.5410993	0.5429096	0.571413
19	0.1552222	0.2108017	0.2658552	0.3108644	0.3478877	0.3812115	0.4106578	0.439034	0.4656665	0.4908553
20	0.1381233	0.1867549	0.2400868	0.2782248	0.311088	0.34078	0.3682885	0.3934889	0.4173989	0.4398945
21	0.1227992	0.1661007	0.2121955	0.2566344	0.2861928	0.3133814	0.3388634	0.3620115	0.3839775	0.404745
22	0.1240689	0.1754564	0.2142922	0.2481722	0.2774755	0.3020948	0.3263014	0.3509668	0.372258	0.3923995
23	0.117821	0.1665844	0.2034072	0.2355042	0.2634555	0.2869061	0.3101728	0.3332498	0.3534462	0.3725302
24	0.1235857	0.1661829	0.2041218	0.230914	0.2547231	0.2774601	0.2999068	0.3216457	0.341274	0.3612366
25	0.1185239	0.1642822	0.1998412	0.22121	0.2417845	0.2634197	0.2846911	0.3052777	0.3238471	0.3413254
26	0.1148169	0.1532864	0.1912128	0.2116042	0.2312634	0.2516695	0.2699197	0.2892721	0.307112	0.3238417
27	0.1103345	0.1551174	0.1918782	0.2123697	0.21907	0.2403391	0.2571133	0.2762348	0.2935594	0.3095035
28	0.1047977	0.1503355	0.1825577	0.2010187	0.2081134	0.2286778	0.2455881	0.2650854	0.2818218	0.2984087
29	0.1033092	0.1419643	0.1812131	0.2008423	0.2067739	0.2265615	0.2426812	0.2604242	0.2768744	0.2933969
30	0.1023922	0.1411966	0.1804644	0.2007958	0.2055576	0.2247232	0.2404956	0.2583549	0.2753155	0.2901838

Table 4-37 Factor K versus number of teeth and load for rough ground and 1020 low carbon steel gear, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

	K(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.4207995	0.603358	0.739232	0.853501	0.9543449	1.048431	1.1291359	1.27178	1.280387	1.3496841
18	0.2981771	0.3956247	0.4812524	0.4783482	0.5329586	0.583367	0.6321441	0.6736469	0.7145128	0.7531629
19	0.1787875	0.250012	0.3062201	0.38387	0.3953594	0.433032	0.46773	0.5000024	0.5293555	0.5580444
20	0.1293355	0.1820936	0.224405	0.25871	0.2892477	0.3169554	0.3422242	0.3657872	0.3880006	0.4095257
21	0.1060911	0.1500396	0.183755	0.212182	0.2372977	0.2598693	0.2806911	0.2997711	0.318274	0.33548
22	0.099842	0.1273077	0.155576	0.179642	0.2008847	0.2200137	0.2376543	0.2540554	0.2696915	0.2847481
23	0.0870722	0.1085911	0.132886	0.153442	0.1715555	0.1878328	0.2029955	0.2170022	0.2301905	0.2426115
24	0.0662955	0.092755	0.1143205	0.13259	0.14824	0.162388	0.1752983	0.187511	0.198934	0.2095642
25	0.0669334	0.0933945	0.1162789	0.1178677	0.12178	0.1443577	0.1559724	0.166811	0.1768011	0.1865985
26	0.062232	0.0874698	0.0914887	0.110564	0.1180108	0.1293382	0.1397845	0.1495419	0.1585455	0.1673031
27	0.0470114	0.0656488	0.0814301	0.0847568	0.105107	0.1115181	0.1204388	0.1302977	0.1410143	0.1498972
28	0.0439096	0.0606949	0.0748948	0.0826132	0.0865987	0.1035964	0.1114522	0.1218803	0.1282039	0.1362282
29	0.0394965	0.0555756	0.0684158	0.0758982	0.0883216	0.0967455	0.1044977	0.1117152	0.1184488	0.1246866
30	0.0386864	0.0548868	0.0682325	0.0751867	0.0804662	0.0881421	0.0952033	0.1017777	0.1079651	0.11379

Table 4-38 Factor K versus number of teeth and load for fine ground and 1020 low carbon steel gear, gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at maximum surface temperature

	K(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.045395	0.022697	0.015132	0.011349	0.009079	0.007566	0.006485	0.005674	0.005044	0.004539
18	0.036272	0.018136	0.012091	0.009068	0.007254	0.006045	0.005182	0.004534	0.004030	0.003627
19	0.032019	0.01601	0.010673	0.008005	0.006404	0.005337	0.004574	0.004002	0.003558	0.003202
20	0.027368	0.013684	0.009123	0.006842	0.005474	0.004561	0.00391	0.003421	0.003041	0.002737
21	0.023741	0.01187	0.007914	0.005935	0.004748	0.003957	0.003392	0.002968	0.002638	0.002374
22	0.021506	0.010753	0.007169	0.005377	0.004301	0.003584	0.003072	0.002688	0.00239	0.002151
23	0.018932	0.009466	0.006311	0.004733	0.003786	0.003155	0.002705	0.002366	0.002104	0.001893
24	0.016776	0.008388	0.005592	0.004194	0.003355	0.002796	0.002397	0.002097	0.001864	0.001678
25	0.015324	0.007662	0.00511	0.003831	0.003065	0.002554	0.002189	0.001916	0.001703	0.001532
26	0.013697	0.006849	0.004566	0.003424	0.002739	0.002283	0.001957	0.001712	0.001522	0.00137
27	0.012285	0.006143	0.004095	0.003074	0.00246	0.00205	0.001757	0.001537	0.001366	0.00123
28	0.011306	0.005653	0.003769	0.002827	0.002261	0.001884	0.001615	0.001413	0.001256	0.001131
29	0.010218	0.005109	0.003406	0.002555	0.002044	0.001703	0.00146	0.001277	0.001135	0.001022
30	0.009267	0.004633	0.003089	0.002317	0.001853	0.001544	0.001324	0.001159	0.00103	0.000927

Table 4-39 Factor K versus number of teeth and load for fine ground and 1020 low carbon steel gear, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

	K(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.237855	0.336095	0.411831	0.475311	0.531414	0.582134	0.628777	0.672191	0.712966	0.751532
18	0.147189	0.20811	0.254991	0.294311	0.32909	0.360456	0.389337	0.416215	0.441457	0.465347
19	0.01606	0.00940	0.00582	0.004245	0.003396	0.00283	0.002426	0.002123	0.001887	0.001698
20	0.007334	0.003887	0.002445	0.001834	0.001467	0.001222	0.001048	0.000917	0.000815	0.000733
21	0.006724	0.002382	0.001575	0.001181	0.000945	0.000787	0.000675	0.000591	0.000525	0.000472
22	0.003401	0.001731	0.001154	0.000865	0.000692	0.000577	0.000494	0.000433	0.000385	0.000346
23	0.002709	0.001354	0.000903	0.000677	0.000542	0.000451	0.000387	0.000338	0.000301	0.000271
24	0.002205	0.001102	0.000735	0.000551	0.000451	0.000367	0.000315	0.000276	0.00245	0.00022
25	0.001823	0.000911	0.000608	0.000456	0.000365	0.000304	0.00026	0.000228	0.000203	0.000182
26	0.001536	0.000769	0.000512	0.000384	0.000307	0.000256	0.000219	0.000192	0.000171	0.000154
27	0.001301	0.00065	0.000434	0.000325	0.00026	0.000217	0.000186	0.000163	0.000145	0.00013
28	0.001113	0.000556	0.000372	0.000278	0.000223	0.000186	0.000159	0.00139	0.00124	0.000112
29	0.000967	0.000483	0.000322	0.000242	0.000193	0.000161	0.000138	0.000121	0.000107	9.67E-05
30	0.000845	0.000422	0.000282	0.000211	0.000169	0.000141	0.000121	0.000106	9.39E-05	8.45E-05

Table 4-40 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 4340 high carbon steel gear gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at inlet temperature

	1/(1+K)^.5(4340 High hardness Steal)									
Ng	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.648161	0.576217	0.552851	0.700902	0.744379	0.773683	0.795890	0.813494	0.828185	0.844442
18	0.644235	0.575032	0.747903	0.722044	0.803381	0.846355	0.864084	0.878054	0.889453	0.898946
19	0.823225	0.747099	0.705811	0.847277	0.872068	0.890612	0.903629	0.914081	0.922548	0.929467
20	0.687670	0.801332	0.858079	0.898549	0.904275	0.918333	0.928785	0.936643	0.942903	0.948534
21	0.749413	0.84154	0.892719	0.918587	0.926513	0.937679	0.945871	0.952155	0.957136	0.961176
22	0.788963	0.872252	0.90625	0.936001	0.943482	0.951294	0.957464	0.962678	0.9668	0.969972
23	0.819888	0.896084	0.92697	0.943710	0.954218	0.961411	0.966851	0.970838	0.973773	0.976094
24	0.847774	0.914219	0.940832	0.9544	0.963021	0.9689	0.973166	0.976402	0.978942	0.980968
25	0.871482	0.92814	0.951501	0.96262	0.96978	0.97401	0.978119	0.98778	0.982667	0.984553
26	0.890002	0.940785	0.959341	0.969229	0.975001	0.979038	0.982082	0.984154	0.985878	0.987263
27	0.907574	0.950148	0.965626	0.974117	0.979123	0.98252	0.984901	0.986804	0.988249	0.989472
28	0.920408	0.957732	0.97122	0.97861	0.982431	0.985285	0.987296	0.98931	0.990124	0.991199
29	0.931902	0.963931	0.975517	0.981469	0.985092	0.987531	0.989284	0.990684	0.991835	0.992462
30	0.940777	0.969034	0.978034	0.984152	0.987261	0.98935	0.990851	0.991951	0.992862	0.993569

Table 4-41 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 4340 high carbon steel gear gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at inlet temperature

	1/(1+K)^.5(4340 High hardness Steal)									
Ng	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.672952	0.607612	0.565564	0.641928	0.512787	0.805557	0.486123	0.475802	0.468018	0.455451
18	0.768248	0.718321	0.673726	0.647306	0.622905	0.608494	0.5937	0.580858	0.569295	0.559395
19	0.80831	0.755893	0.721892	0.695552	0.673096	0.653446	0.845908	0.633282	0.621177	0.611179
20	0.846922	0.800309	0.765813	0.748642	0.727878	0.712175	0.698418	0.686394	0.675632	0.665914
21	0.863128	0.824521	0.795278	0.774759	0.7571035	0.742938	0.729132	0.717621	0.707282	0.697902
22	0.882962	0.845286	0.81234	0.795272	0.779251	0.768033	0.756385	0.745455	0.735038	0.725542
23	0.896394	0.862054	0.834143	0.819496	0.804061	0.790828	0.779222	0.768368	0.758005	0.750356
24	0.907557	0.876122	0.8541811	0.836772	0.822349	0.80963	0.796952	0.787202	0.778138	0.772201
25	0.916884	0.888024	0.89765	0.851522	0.838534	0.826372	0.8160745	0.806823	0.798415	0.7967
26	0.9246581	0.89845	0.879172	0.864126	0.8521492	0.8403434	0.8308222	0.822075	0.814112	0.8007877
27	0.931265	0.906871	0.889667	0.874997	0.86214	0.852824	0.843657	0.835389	0.827834	0.8210877
28	0.93776	0.9142677	0.8977889	0.8849141	0.8734722	0.863785	0.85514	0.847278	0.840122	0.8339149
29	0.941669	0.919724	0.9053429	0.8933844	0.882508	0.872339	0.863121	0.8557735	0.8509411	0.8446861
30	0.9462161	0.9263477	0.9118222	0.9002721	0.8903889	0.88189	0.8733911	0.8663962	0.8598226	0.8544448

Table 4-42 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 4340 high carbon steel gear, gear ratio Mg=2. center distance Cd=10 and constant oil viscosity at inlet temperature

	1/(1+K)^.5(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.945512	0.786677	0.825733	0.809672	0.903611	0.900457	0.912877	0.922537	0.930265	0.93658
18	0.712264	0.822453	0.869157	0.85702	0.915674	0.927739	0.93706	0.944324	0.950055	0.954719
19	0.7649	0.853208	0.893334	0.92163	0.935832	0.945872	0.952894	0.95842	0.962769	0.966302
20	0.806348	0.88504	0.921383	0.939051	0.95235	0.959113	0.963776	0.96719	0.971483	0.974527
21	0.849453	0.908898	0.937174	0.951765	0.962954	0.96709	0.971567	0.974989	0.977678	0.979841
22	0.897479	0.926787	0.948315	0.961264	0.968651	0.973672	0.977306	0.980068	0.982215	0.983951
23	0.949302	0.939796	0.95844	0.968487	0.97456	0.978985	0.98163	0.983871	0.985824	0.987634
24	0.977001	0.959184	0.965697	0.974095	0.978115	0.982546	0.984948	0.986782	0.988234	0.989366
25	0.921425	0.968326	0.971618	0.978487	0.982679	0.985903	0.987535	0.989008	0.990285	0.991227
26	0.93241	0.964855	0.978181	0.981575	0.985503	0.987875	0.98998	0.990985	0.991958	0.992772
27	0.942872	0.970231	0.98657	0.984778	0.987787	0.989775	0.991212	0.99239	0.993148	0.993827
28	0.9513	0.974583	0.982848	0.987151	0.989601	0.991312	0.992535	0.993462	0.994183	0.99476
29	0.957738	0.978185	0.984287	0.989512	0.9911	0.992507	0.993619	0.99441	0.995056	0.99552
30	0.963352	0.98163	0.987323	0.990447	0.992436	0.993601	0.994515	0.995189	0.99572	0.996146

Table 4-43 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 4340 high carbon steel gear, gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

	1/(1+K)^.5(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.917334	0.955068	0.969248	0.943148	0.953744	0.961089	0.966301	0.970328	0.973485	0.976021
18	0.940946	0.966535	0.97876	0.883443	0.967042	0.972899	0.97725	0.980716	0.983487	0.985683
19	0.958758	0.975057	0.983541	0.991269	0.983077	0.984221	0.98504	0.985858	0.986438	0.986881
20	0.973517	0.980953	0.987032	0.994407	0.99559	0.986321	0.986944	0.987237	0.987543	0.987795
21	0.9888 13	0.985422	0.989188	0.996185	0.996349	0.997455	0.987817	0.988031	0.988201	0.98847
22	0.9888037	0.9944 73	0.990356	0.997225	0.997778	0.998147	0.998412	0.98861	0.988764	0.988887
23	0.991739	0.995829	0.997213	0.997958	0.998325	0.998604	0.998812	0.998852	0.989069	0.989162
24	0.993871	0.99577	0.997843	0.998361	0.998704	0.99892	0.999074	0.99919	0.999279	0.999351
25	0.994914	0.997447	0.998289	0.999721	0.999977	0.999147	0.999263	0.99936	0.999431	0.999485
26	0.995011	0.997545	0.998331	0.999373	0.999178	0.999318	0.999419	0.999496	0.999543	0.999599
27	0.995607	0.998376	0.998585	0.999164	0.999331	0.999442	0.999522	0.999582	0.999628	0.999665
28	0.997251	0.998922	0.999081	0.99931	0.999448	0.99954	0.999606	0.999659	0.999692	0.999724
29	0.997769	0.998852	0.999234	0.999426	0.99954	0.999617	0.999672	0.999713	0.999745	0.99977
30	0.998078	0.999036	0.999356	0.999517	0.999614	0.999678	0.999724	0.999758	0.999785	0.999807

Table 4-44 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 1020 low carbon steel gear gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at inlet temperature

	1/(1+K)^.5(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.628172	0.752201	0.81341	0.850183	0.874756	0.892304	0.905064	0.919015	0.924315	0.931121
18	0.724325	0.829551	0.878370	0.902851	0.920104	0.932097	0.940056	0.947769	0.953172	0.957561
19	0.790471	0.876891	0.91282	0.932464	0.944878	0.953434	0.95989	0.964483	0.968226	0.971268
20	0.837707	0.909163	0.935902	0.950765	0.960031	0.96636	0.970959	0.974451	0.977193	0.979404
21	0.872286	0.929633	0.951413	0.962894	0.969984	0.9748	0.978283	0.980921	0.982987	0.984646
22	0.899122	0.944967	0.96229	0.971316	0.976855	0.980601	0.983304	0.985345	0.986942	0.988225
23	0.917724	0.956218	0.970167	0.977374	0.981776	0.984745	0.986881	0.988493	0.989752	0.990763
24	0.932810	0.964659	0.97602	0.981853	0.985403	0.987792	0.989509	0.990802	0.991811	0.992621
25	0.944584	0.971113	0.980462	0.985239	0.988130	0.990087	0.991485	0.992537	0.993358	0.994016
26	0.953888	0.976128	0.983895	0.987849	0.990243	0.991849	0.993001	0.993868	0.994544	0.995086
27	0.961304	0.98008	0.986587	0.98958	0.991587	0.993226	0.994185	0.994906	0.995468	0.995919
28	0.96720	0.983232	0.988727	0.99151	0.99318	0.994316	0.995122	0.995728	0.9962	0.996578
29	0.972130	0.985775	0.990449	0.992811	0.994236	0.99519	0.995873	0.996385	0.996786	0.997108
30	0.976124	0.987846	0.991848	0.993867	0.995086	0.995899	0.996482	0.996919	0.99726	0.997533

Table 4-45 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 1020 low carbon steel gear, gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

	1/(1+K)^.5(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.827415	0.778147	0.745769	0.721434	0.701845	0.685443	0.671333	0.658953	0.647928	0.637994
18	0.899196	0.852965	0.826014	0.804564	0.792553	0.775852	0.76666	0.756182	0.748540	0.737758
19	0.912	0.881769	0.860541	0.843773	0.829785	0.817718	0.807078	0.797535	0.788975	0.780038
20	0.931963	0.907584	0.890121	0.876158	0.864365	0.85414	0.845034	0.836814	0.829380	0.822380
21	0.941986	0.920747	0.90539	0.893023	0.882534	0.873369	0.865185	0.857771	0.850976	0.8447
22	0.950107	0.931521	0.917877	0.907006	0.89766	0.889455	0.882104	0.875423	0.869285	0.863597
23	0.956406	0.93965	0.927881	0.918061	0.909682	0.902264	0.895618	0.889562	0.883985	0.878805
24	0.961523	0.946837	0.936013	0.927171	0.919585	0.912885	0.906851	0.901341	0.896256	0.891526
25	0.965707	0.9525	0.942726	0.934718	0.927825	0.921725	0.91622	0.911184	0.906529	0.902181
26	0.969164	0.957187	0.9483	0.940997	0.9347	0.929118	0.924067	0.919441	0.915150	0.911164
27	0.972038	0.961121	0.952991	0.946295	0.94051	0.935372	0.930710	0.926451	0.922405	0.91858
28	0.974510	0.96452	0.957053	0.950801	0.945650	0.940918	0.936510	0.932567	0.928902	0.925470
29	0.976831	0.96742	0.960527	0.954820	0.94989	0.945492	0.941501	0.937831	0.934422	0.931233
30	0.978490	0.969594	0.963498	0.958197	0.953561	0.949502	0.94578	0.942354	0.939189	0.936167

Table 4-46 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 1020 low carbon steel gear, gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at inlet temperature

	1/(1+K)^.5(1020 low hardness Steel)									
Ng	HP=10	HP=25	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.887455	0.883445	0.8813084	0.8739	0.866841	0.860782	0.855323	0.850321	0.845703	0.841404
18	0.894265	0.890573	0.8873487	0.8809787	0.875147	0.870501	0.866255	0.86243	0.858941	0.855722
19	0.900211	0.896861	0.8937865	0.8878211	0.882101	0.877192	0.872617	0.868319	0.864267	0.860437
20	0.911188	0.882508	0.8875875	0.875363	0.8801653	0.883389	0.8957	0.887464	0.8808834	0.8745393
21	0.9238074	0.8825837	0.8745453	0.8637895	0.8534819	0.8437847	0.8346997	0.8260238	0.8178397	0.8102169
22	0.9420642	0.9700352	0.979733	0.9846844	0.9879691	0.9907111	0.9931152	0.9952754	0.9931165	0.9837383
23	0.953916	0.975706	0.9836666	0.9876629	0.990956	0.9917026	0.9922874	0.9933787	0.9944445	0.9943698
24	0.991271	0.9933062	0.9965579	0.99858	0.9991851	0.9993216	0.99818	0.9964802	0.9934484	0.9859188
25	0.99773	0.9834484	0.988837	0.9918331	0.9932269	0.9943367	0.9951182	0.9957796	0.9962254	0.996627
26	0.972892	0.986188	0.9937114	0.9930011	0.9943277	0.9953324	0.9961668	0.9968747	0.9974876	0.9977187
27	0.977957	0.9825326	0.9921714	0.9941133	0.9958292	0.9963964	0.9968233	0.9971944	0.9975731	0.9975833
28	0.980848	0.98000	0.9833254	0.9953963	0.9967588	0.99686	0.997136	0.9974482	0.99777	0.9977892
29	0.983234	0.9918111	0.9943116	0.9957728	0.996578	0.9971468	0.9975502	0.9978957	0.9980098	0.9982285
30	0.985534	0.99268	0.9951109	0.996325	0.9972857	0.9975478	0.9977855	0.9981627	0.9983602	0.9985251

Table 4-47 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 1020 low carbon steel gear gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at inlet temperature

	1/(1+K)^.5(1020 low hardness Steel)									
Ng	HP=10	HP=28	HP=38	HP=48	HP=58	HP=68	HP=78	HP=88	HP=98	HP=108
17	0.916924	0.855768	0.869851	0.877132	0.91199	0.96458	0.987739	0.9853	0.98454	0.9804
18	0.875814	0.887655	0.901739	0.893765	0.955016	0.995844	0.990834	0.988778	0.9872	0.9875
19	0.886974	0.893998	0.905884	0.896652	0.957343	0.997785	0.9881	0.988337	0.9868	0.9866
20	0.918643	0.885793	0.897181	0.9078	0.968312	0.938592	0.988783	0.988444	0.990061	0.99187
21	0.9042935	0.89758	0.9048557	0.9165	0.9755333	0.939087	0.989166	0.99027	0.988351	0.9904119
22	0.965777	0.9978	0.9915	0.9955	0.9791151	0.9912	0.9923	0.9934	0.9945	0.9956
23	0.998114	0.99403	0.999038	0.995201	0.99536	0.991467	0.988543	0.9856	0.999645	0.99493
24	0.887534	0.982765	0.885176	0.993382	0.988508	0.983548	0.9936447	0.999911	0.999725	0.999753
25	0.998552	0.999624	0.999349	0.998512	0.999609	0.999674	0.9997211	0.999758	0.999783	0.9998084
26	0.999835	0.999211	0.999477	0.999608	0.999689	0.999739	0.9997776	0.999804	0.999818	0.999843
27	0.999729	0.9997362	0.9998574	0.9998781	0.9997453	0.999787	0.9998116	0.99984	0.9998561	0.9998772
28	0.9998948	0.999474	0.9998649	0.9997737	0.99976	0.9998205	0.99985	0.9998663	0.9998853	0.9998995
29	0.9998124	0.9998562	0.9997008	0.9998781	0.9998325	0.9998564	0.9998478	0.99989	0.9998953	0.9998112
30	0.9998364	0.999834	0.9997864	0.9998818	0.9998553	0.9998777	0.9998685	0.9999008	0.9998818	0.9998926

Table 4-48 design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 4340 high carbon steel gear, gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at maximum surface temperature

	1/(1+K)^.5(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.781206	0.736236	0.701043	0.674084	0.6543	0.637142	0.6225	0.609074	0.598444	0.588316
18	0.823694	0.773778	0.741083	0.716519	0.696788	0.680206	0.665101	0.653665	0.642599	0.632632
19	0.843024	0.796641	0.765615	0.742439	0.723523	0.707611	0.693846	0.681771	0.670866	0.661206
20	0.855984	0.813174	0.782789	0.760346	0.742894	0.728678	0.713315	0.701519	0.690956	0.681368
21	0.865267	0.823468	0.795205	0.773513	0.755803	0.740797	0.727759	0.716221	0.70587	0.696442
22	0.868604	0.827542	0.790704	0.776797	0.760796	0.74595	0.733038	0.721603	0.711337	0.702619
23	0.874038	0.854206	0.807082	0.788161	0.769017	0.754446	0.741753	0.730480	0.720378	0.711184
24	0.868873	0.927617	0.940571	0.961771	0.969067	0.974023	0.97761	0.980327	0.982456	0.984169
25	0.904044	0.9484	0.964703	0.973176	0.978368	0.981678	0.984405	0.986314	0.987807	0.989087
26	0.925177	0.960409	0.973079	0.979006	0.983554	0.986264	0.988122	0.989645	0.99078	0.99169
27	0.939871	0.968536	0.978093	0.983892	0.987061	0.989175	0.9907	0.991848	0.992744	0.993482
28	0.950589	0.974356	0.982684	0.986928	0.989502	0.991228	0.992467	0.9934	0.994127	0.994708
29	0.958547	0.978815	0.985591	0.989134	0.991279	0.992717	0.993748	0.994523	0.995127	0.995611
30	0.964728	0.981888	0.987816	0.99082	0.992136	0.993852	0.994723	0.995378	0.995868	0.996288

Table 4-49 design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 4340 high carbon steel gear, gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at maximum surface temperature

	1/(1+K)^.5(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.666914	0.622217	0.58334	0.555673	0.534304	0.516967	0.502430	0.489843	0.478026	0.468346
18	0.784555	0.728675	0.693061	0.666777	0.64584	0.628633	0.613993	0.601109	0.589683	0.579747
19	0.826677	0.777162	0.744727	0.730325	0.700783	0.684278	0.67015	0.657758	0.646723	0.636781
20	0.864111	0.822068	0.793052	0.771863	0.754083	0.739023	0.725842	0.71437	0.703881	0.69458
21	0.884484	0.847138	0.821463	0.801548	0.785153	0.771165	0.75884	0.748069	0.738273	0.729353
22	0.899636	0.866088	0.842746	0.824469	0.809314	0.796509	0.784868	0.774568	0.765459	0.757027
23	0.912411	0.882315	0.861139	0.844435	0.830478	0.818446	0.807831	0.798314	0.789874	0.781755
24	0.922977	0.895904	0.876873	0.861389	0.848563	0.837449	0.827685	0.818746	0.810682	0.803269
25	0.930662	0.905885	0.888159	0.873898	0.862087	0.851881	0.842473	0.834156	0.826565	0.819573
26	0.937192	0.914433	0.898051	0.884904	0.873787	0.864089	0.85545	0.847836	0.840482	0.833897
27	0.943522	0.922776	0.907758	0.895646	0.88537	0.876377	0.868345	0.861084	0.854359	0.848217
28	0.947887	0.92854	0.914495	0.903121	0.893452	0.884072	0.877384	0.870403	0.864197	0.858309
29	0.951014	0.933932	0.920865	0.910158	0.901077	0.893098	0.885944	0.879437	0.873498	0.867907
30	0.955912	0.938284	0.927087	0.917104	0.908708	0.901245	0.894541	0.888435	0.882811	0.87759

Table 4-50 design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 4340 high carbon steel gear gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at maximum surface temperature

	1/(1+K)^.5(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.945311	0.971803	0.98073	0.985443	0.988303	0.990224	0.991583	0.992641	0.993451	0.9941
18	0.955562	0.977035	0.984513	0.988217	0.990521	0.992168	0.993274	0.994187	0.994757	0.995277
19	0.963435	0.981048	0.987548	0.990892	0.991787	0.993075	0.994053	0.994793	0.995367	0.995808
20	0.969936	0.984295	0.989648	0.991747	0.992898	0.994072	0.994912	0.995544	0.996036	0.99642
21	0.97525	0.986988	0.991282	0.992907	0.993831	0.994551	0.995132	0.995631	0.996039	0.996361
22	0.979239	0.989161	0.99273	0.993923	0.994487	0.995033	0.995595	0.996033	0.996401	0.996702
23	0.982833	0.991214	0.993826	0.994826	0.995072	0.995458	0.995972	0.996311	0.996723	0.997027
24	0.986701	0.993178	0.994747	0.995548	0.995628	0.996354	0.996672	0.997051	0.997305	0.997597
25	0.989452	0.995102	0.995809	0.996514	0.996905	0.996908	0.997142	0.997458	0.997778	0.997967
26	0.992509	0.9961136	0.996964	0.99754	0.998427	0.99792	0.997464	0.997762	0.99801	0.998265
27	0.994254	0.997033	0.997488	0.998093	0.99779	0.997323	0.997704	0.99789	0.998213	0.998381
28	0.995488	0.997868	0.998094	0.998314	0.997548	0.997838	0.997884	0.998162	0.998357	0.998621
29	0.996864	0.998367	0.998563	0.998687	0.998731	0.997774	0.998091	0.998324	0.998515	0.998663
30	0.998045	0.998979	0.998974	0.998978	0.997978	0.997981	0.998269	0.998434	0.998583	0.998787

Table 4-51 design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 4340 high carbon steel gear gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at maximum surface temperature

	1/(1+K)^.5(4340 High hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.784881	0.879648	0.893481	0.867178	0.946349	0.928164	0.614407	0.601815	0.592289	0.580164
18	0.849433	0.904313	0.774182	0.751251	0.732651	0.716073	0.70341	0.691454	0.682762	0.671093
19	0.878451	0.889049	0.90263	0.904479	0.885578	0.956309	0.896834	0.887228	0.997836	0.987781
20	0.909519	0.995228	0.996809	0.957604	0.948482	0.938491	0.930629	0.90194	0.996833	0.99004
21	0.903652	0.995917	0.957941	0.958859	0.998783	0.993869	0.989115	0.985027	0.9808312	0.9893381
22	0.999402	0.997736	0.994491	0.998017	0.993198	0.998144	0.983352	0.979433	0.996938	0.993649
23	0.936477	0.994229	0.998118	0.998113	0.99829	0.995478	0.992423	0.990505	0.996056	0.9990649
24	0.997122	0.995598	0.999038	0.998278	0.995422	0.999519	0.996587	0.998535	0.999678	0.9997111
25	0.997619	0.998407	0.998204	0.998403	0.998522	0.999502	0.999659	0.997701	0.995738	0.9997751
26	0.997962	0.998989	0.999329	0.999407	0.999687	0.999665	0.999712	0.9997748	0.998776	0.9997996
27	0.998288	0.999149	0.999432	0.999574	0.999655	0.999719	0.998788	0.999757	0.999811	0.9998427
28	0.99854	0.999269	0.999513	0.999654	0.999709	0.999756	0.998791	0.999817	0.999857	0.9998654
29	0.998735	0.999367	0.999578	0.999683	0.999747	0.999786	0.999818	0.999842	0.999859	0.9998879
30	0.998894	0.999487	0.999631	0.999723	0.999778	0.999815	0.999842	0.999862	0.999877	0.9998989

Table 4-52 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 1020 low carbon steel gear, gear ratio Mg=2 center distance Cd=10 and constant oil viscosity at maximum surface temperature

	1/(1+K)^.5(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.902479	0.82986	0.840804	0.828869	0.81396	0.80110	0.789906	0.778847	0.770741	0.7624156
18	0.920302	0.892449	0.872712	0.857853	0.843933	0.832577	0.822528	0.813494	0.805275	0.7977265
19	0.930305	0.906537	0.887758	0.873566	0.861595	0.85110	0.841949	0.833813	0.826006	0.818997
20	0.936946	0.91411	0.897679	0.88449	0.873341	0.863617	0.854906	0.847123	0.83906	0.8233492
21	0.941554	0.920182	0.904732	0.892294	0.881751	0.872535	0.864309	0.856858	0.850033	0.8437257
22	0.943192	0.922341	0.907247	0.896082	0.88476	0.875729	0.867064	0.860354	0.853654	0.8474582
23	0.945632	0.925837	0.911328	0.899609	0.889652	0.880929	0.87313	0.866053	0.8595	0.8533537
24	0.943372	0.979449	0.980006	0.984882	0.987559	0.989652	0.991283	0.99236	0.9932	0.9936736
25	0.950025	0.979348	0.986080	0.989512	0.991584	0.992972	0.993987	0.994715	0.995298	0.9957851
26	0.960382	0.984334	0.989474	0.992074	0.993644	0.994695	0.995449	0.996013	0.996454	0.9968069
27	0.975738	0.987840	0.991713	0.993765	0.995003	0.995831	0.996423	0.996856	0.997215	0.997480
28	0.980004	0.989985	0.99329	0.994856	0.995858	0.996528	0.997108	0.997469	0.997748	0.9972727
29	0.983569	0.991882	0.994431	0.995815	0.996069	0.997204	0.997602	0.997801	0.998133	0.9983186
30	0.986004	0.992977	0.996301	0.99647	0.997173	0.997842	0.997978	0.99843	0.998425	0.9985834

Table 4-53 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for rough ground and 1020 low carbon steel gear, gear ratio Mg=10 center distance Cd=10 and constant oil viscosity at maximum surface temperature

	1/(1+K)^.5(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.837191	0.789686	0.768266	0.734502	0.715316	0.69921	0.685318	0.673105	0.66221	0.6523772
18	0.88869	0.854894	0.841305	0.823013	0.807775	0.794783	0.783827	0.772979	0.762712	0.7552469
19	0.921631	0.894423	0.874974	0.859527	0.846575	0.835356	0.825424	0.81649	0.808358	0.8008563
20	0.940989	0.919432	0.903456	0.891327	0.880728	0.871427	0.863147	0.855646	0.84878	0.8424336
21	0.950534	0.93249	0.919113	0.908272	0.899032	0.890917	0.883645	0.877034	0.870958	0.8653359
22	0.957005	0.941881	0.930253	0.920714	0.912540	0.905351	0.89886	0.89219	0.887544	0.8824917
23	0.963714	0.9498	0.939522	0.931112	0.923867	0.917497	0.911737	0.906472	0.901606	0.897091
24	0.966415	0.954191	0.947101	0.939045	0.933210	0.927522	0.922374	0.917656	0.913290	0.9092252
25	0.971775	0.959764	0.952564	0.945812	0.920651	0.934601	0.930112	0.925811	0.921825	0.918102
26	0.974592	0.964621	0.957174	0.951028	0.94571	0.940679	0.936859	0.932749	0.929094	0.9250756
27	0.977201	0.968327	0.961014	0.956061	0.951246	0.946956	0.943066	0.939484	0.936158	0.9330436
28	0.979124	0.970852	0.964645	0.959503	0.955041	0.95106	0.947443	0.944113	0.941017	0.9381165
29	0.980818	0.97319	0.967456	0.9627	0.958567	0.954978	0.95152	0.948427	0.945848	0.9428519
30	0.98248	0.975487	0.970222	0.965848	0.962045	0.958694	0.955544	0.952693	0.950035	0.9475416

Table 4-54 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 1020 low carbon steel gear, gear ratio Mg=2, center distance Cd=10 and constant oil viscosity at maximum surface temperature

	1/(1+K)^.5(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.979047	0.988841	0.992519	0.994373	0.995401	0.996238	0.996773	0.997175	0.997488	0.997760
18	0.982343	0.991054	0.994009	0.995407	0.996450	0.997001	0.997410	0.997741	0.997981	0.998181
19	0.984306	0.99209	0.994706	0.996021	0.996813	0.997343	0.997721	0.998009	0.998220	0.998403
20	0.986591	0.993227	0.99547	0.996596	0.997278	0.997727	0.998081	0.998294	0.998483	0.998634
21	0.988337	0.994117	0.996006	0.997045	0.997634	0.998057	0.998309	0.998518	0.998684	0.998819
22	0.989817	0.994866	0.996435	0.997323	0.997856	0.998213	0.998467	0.998664	0.998807	0.998930
23	0.990906	0.9953	0.99680	0.997642	0.998112	0.998426	0.99865	0.998779	0.998885	0.998995
24	0.991710	0.995832	0.997210	0.99791	0.998327	0.998606	0.998864	0.998963	0.999068	0.999182
25	0.992825	0.996191	0.997450	0.99805	0.998471	0.998725	0.998907	0.999046	0.99915	0.999235
26	0.993221	0.996583	0.997726	0.998202	0.998533	0.998841	0.999023	0.999185	0.99924	0.999318
27	0.993087	0.99694	0.997957	0.998466	0.998772	0.998977	0.999123	0.999230	0.999317	0.999386
28	0.994384	0.997185	0.998121	0.99859	0.998871	0.999058	0.999193	0.999294	0.999372	0.999436
29	0.99483	0.997455	0.998301	0.998725	0.99898	0.99915	0.999271	0.999362	0.999433	0.999459
30	0.995308	0.997681	0.998459	0.998864	0.999075	0.999228	0.999339	0.999401	0.999466	0.999537

Table 4-55 Design factor $1/\sqrt{(1+K)}$ versus number of teeth and load for fine ground and 1020 low carbon steel gear, gear ratio Mg=10, center distance Cd=10 and constant oil viscosity at maximum surface temperature

	1/(1+K)^.5(1020 low hardness Steel)									
Np	HP=10	HP=20	HP=30	HP=40	HP=50	HP=60	HP=70	HP=80	HP=90	HP=100
17	0.958877	0.90513	0.841006	0.8233	0.808979	0.79602	0.783554	0.773318	0.764057	0.755898
18	0.93368	0.909859	0.892686	0.878983	0.86742	0.857348	0.848301	0.840301	0.832909	0.826094
19	0.991810	0.995700	0.997182	0.997884	0.998306	0.998588	0.998791	0.99894	0.999058	0.999152
20	0.995353	0.998171	0.99878	0.999096	0.999287	0.999388	0.999477	0.999542	0.999593	0.999633
21	0.997645	0.998821	0.999218	0.99941	0.999528	0.999607	0.999658	0.999705	0.999738	0.999764
22	0.998278	0.999136	0.999424	0.999568	0.999654	0.999712	0.999753	0.999784	0.999808	0.999827
23	0.998680	0.999323	0.999549	0.999662	0.999729	0.999778	0.999807	0.999831	0.99985	0.999865
24	0.9989	0.999449	0.999633	0.999725	0.99978	0.999816	0.999843	0.999859	0.999878	0.99989
25	0.99909	0.999545	0.999696	0.999772	0.999818	0.999848	0.99987	0.999886	0.999899	0.999909
26	0.999233	0.999616	0.999744	0.999808	0.999846	0.999872	0.99989	0.999904	0.999915	0.999923
27	0.99935	0.999675	0.999783	0.999837	0.99987	0.999891	0.999907	0.999918	0.999928	0.999935
28	0.999443	0.999721	0.999814	0.999861	0.999888	0.999907	0.99992	0.99993	0.999938	0.999944
29	0.999517	0.999758	0.999839	0.999879	0.999903	0.999919	0.999931	0.99994	0.999946	0.999952
30	0.999578	0.999789	0.999859	0.999894	0.999916	0.99993	0.99994	0.999947	0.999953	0.999958

CHAPTER 5
SUMMARY CONCLUSIONS AND RECOMMENDATIONS

Summary

The study reported in this thesis can be summarized as follows

Chapter 1 gives a brief review of the surface failures mechanism such as wear pitting and scoring and the recent studies on surface failures and gear tooth temperature calculations.

Chapter 2 gives relationship for calculating the nominal temperature rise at the start of contact where the maximum sliding/rolling ratio occurs on the gear tooth surface. This temperature is calculated as transient temperature rise along the contact added to the bulk temperature of gear The temperature rise, thermal and contact stresses are defined in dimensionless form. Numerical results are also given for several different geometrical conditions such as center distance, number of teeth and gear ratio All these calculations assume smooth surfaces where the heat input is frictional with a constant coefficient of friction

Chapter 3 gives the dimensionless relationship for the allowable contact stress modification due to thermal stress In this chapter definitions of thermal stress thermal fatigue and thermal shock are given The design criteria for the combined mechanical and the thermal stress is given. Two different materials 1020 low carbon and 4340 high carbon steels are considered Also in this chapter also the numerical calculations are made under the assumption of constant nominal contact area, constant frictional heat input without consideration of the effect of lubrication film Further more studies are

input without consideration of the effect of lubrication film. Further more studies are done for two different cases: one without consideration of the change of ultimate tensile strength with temperature and the other one with consideration of the effect of this change.

Chapter 4 deals with the investigation of the effect of surface roughness and lubrication. In this chapter the effect of the lubricating film thickness (given by Dowson and Higginson) and the surface roughness (given by Greenwood-Williamson model) are considered. The study is applied to the gear surface at the first point of contact where the maximum temperature rise occurs. Also the evaluation of the coefficient of friction based on the oil film thickness is discussed. A procedure is presented for temperature rise calculation based on the analysis developed by Rashid and Seireg. These calculations are undertaken for conditions of frictional heating or viscous heating depending on the surface roughness and lubricating film thickness. The procedure is applied to rough and fine ground gears with following assumptions, which represent the upper and lower limits of viscosity:

a) Constant oil viscosity corresponding to the inlet temperature.

b) Constant oil viscosity corresponding to the maximum bulk surface temperature.

The contact stress modification factors in lubricated rolling/ sliding contacts are calculated by using the same approach given in chapter 3 with the consideration of the lubricating film, the gear material and the surface roughness.

Conclusions

The following can be concluded from the reported study:

The surface temperature rise is significantly increased for low number of pinion teeth and high gear ratios as a result of a high sliding to rolling ratio.

The lower number of teeth and higher load consequently decreases the allowable mechanical stress, as shown in equation (3 8)

The allowable mechanical stress is decreased with the decrease in center distance

The surface roughness has a significant effect on the temperature rise Fine ground gears are generally subjected to viscous heating, which reduces the temperature rise at asperities On the other hand rough ground surfaces are subjected to frictional heating due to the higher asperity height in relation to the oil film thickness.

The load effect on modifying the allowable contact stress is negligible for condition of viscous heating

High carbon steel gears are significantly more sensitive to the thermal stress than low carbon steel because of the significant changes in their ultimate strength changes with temperature and their high susceptibility to thermal fatigue and thermal shock

Recommendation

The following are some recommendations for future studies on this subject

More accurate treatment of the effect of temperature distribution in the contact zone on the viscosity of the lubricating film and the heat generation within the film needs to be considered

Investigation of the effect of the thermal conditions on the physical and chemical changes which take place in the contact zone

Investigation of the effect of the chemical layers that may be generated on surface as well as surface coating with different thermal properties on the surface temperature.

Planning controlled experiments to verify the general findings of this investigation and to point to any significant parameters that may have not been given adequate consideration in the reported study

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